SOME FACTORS AFFECTING THE GAIN AND RESOLUTION OF A PHOTO-MULTIPLIER

A Thesis

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by

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LIST OF FIGURES AND PLATES

PREFACE

The work presented in this thesis was carried out at the Physics Laboratories of the University of Manitoba, Winnipeg (Canada) during September 1957 - March 1959 under the direct supervision and guidance of Dr. R. D. Connor.

The author expresses his deep sense of gratitude to Dr. Connor for his able guidance, constant encouragement and valuable suggestions during the progress of this work. Acknowledgement is also due to Dr. I. L. Fairweather for many helpful suggestions and to Miss Bernnetta Hartland for accepting the typing work.

Financial assistance from the governments of Canada and Pakistan under Colombo Plan is gratefully acknowledged without which the project could not have been undertaken.

ABSTRACT

A study of the variation of gain and resolution of scintillation counters using DuMont photomultipliers with time, axial magnetic field, temperature and counting rate was made in detail. Both slow and sudden changes in gain of a photo-multiplier were observed with time and counting rate respectively. During the study of the change of gain with axial magnetic field of a DuMont-6292 photo-tube the best shielding was obtained with a mild steel pipe extending about 2.0 inches beyond the photo-cathode. Hysteresis effects were also observed in the same tube. The variation in gain with temperature from 0°C to 35°C was found non-linear. For a small change in temperature around normal room temperature, however, the gain was found approximately linear and was about -0.3% per degree centigrade for DuMont-6292 and -2.0% for DuMont-6364. The variation of resolution with γ-ray energy for a 6364 type photomultiplier and a 5" x 4" crystal was found to obey the $\eta^2 = \alpha + \beta/E$ law from 60 keV to > 1.3 MeV, a result not to be expected from recent statistical interpretations of the behaviour of small crystals.

INTRODUCTION

The scintillation photomultiplier counter is an instrument of great importance and interest. The history of the instrument since its inception is largely a history of experimental nuclear physics since that date. In its original visual form, designed and used by Rutherford and his associates in 1903, it played an important role in the development of classical nuclear physics. The scintillation technique was one of the earliest employed for the detection of nuclear emanations. Through the identification of the α-particle and the discovery of the atomic nucleus up to the Cockcroft-Walton experiments, it initiated what we can call the machine age of the modern physics.

The difficulty in counting the light flashes and the discovery of the Geiger Counter (1913) and new electronic devices was, however, responsible for forcing the visual scintillation technique to pass through a dark age lasting about fifteen years, during which it was considered only an instrument of historical importance. The renaissance of the scintillation technique was brought about in 1944 by Curran and Baker with the addition of a photomultiplier tube for the detection of the scintillations. This was the first simple form of the modern scintillation counter.

A survey of the application and uses of the photomultiplier scintillation counter in the field of nuclear physics shows a very wide range of application, versatility of the instrument and its great superiority over the gas counters. In the short period since its introduction in the present form, it has already come to occupy the position of its visual predecessor as one of the most valuable instruments in nuclear physics research.

SCINTILLATION SPECTROMETER

The technique of single crystal γ-ray spectroscopy with NaI(Tl) was initially developed by McIntyre and Hofstadter (1950), Pringle et al. (1950) and Bell and Jordon (1950). The arrangement of the scintillation photo-multiplier tube assembly is given in Fig. 1. It consists of a scintillating material (NaI(Tl) in our case) called the phosphor which gives out flashes of light whenever a nuclear particle interacts with it. As the flashes of light emitted by the phosphor are very minute and short lived, the scintillator is coupled directly or through a light-pipe to a photo-multiplier tube. The light pipe is used to cause a somewhat more uniform illumination of the photo-cathode surface of the multiplier tube, more or less independent of the position of the origin of the scintillation in the phosphor. It also sometimes helps to remove the photomultiplier tube from an unsuitable location e.g., in a magnetic field. The light flash emitted by the phosphor falls on the photo-cathode of the photo-multiplier and the photons constituting the flash of light eject electrons from it. These photo-electrons are accelerated by the potential applied between the cathode and the first electrode (or dynode) of the tube. On striking the first dynode, each photo-electron ejects several further electrons by the process of secondary emission. This electron multi-

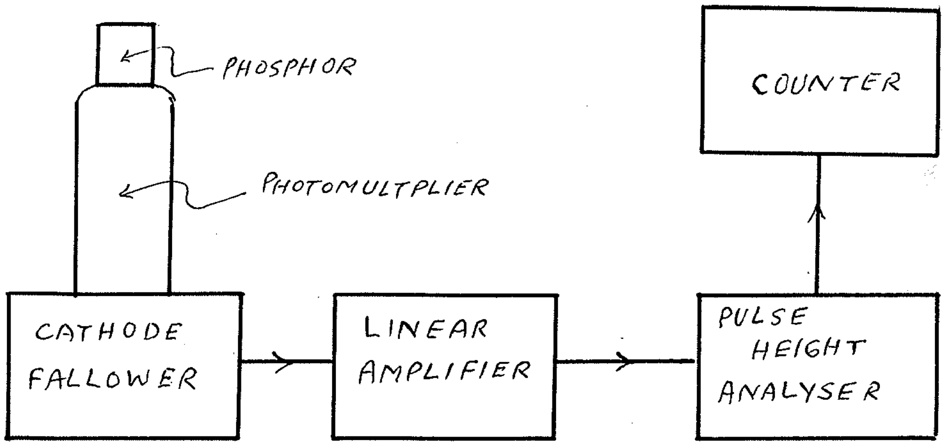

PHOSPHOR
PHOTOMULTPLIER
CATHODE FALLOWER
LINEAR AMPLIFIER
PULSE HEIGHT ANALYSER
COUNTER

FIG. 2

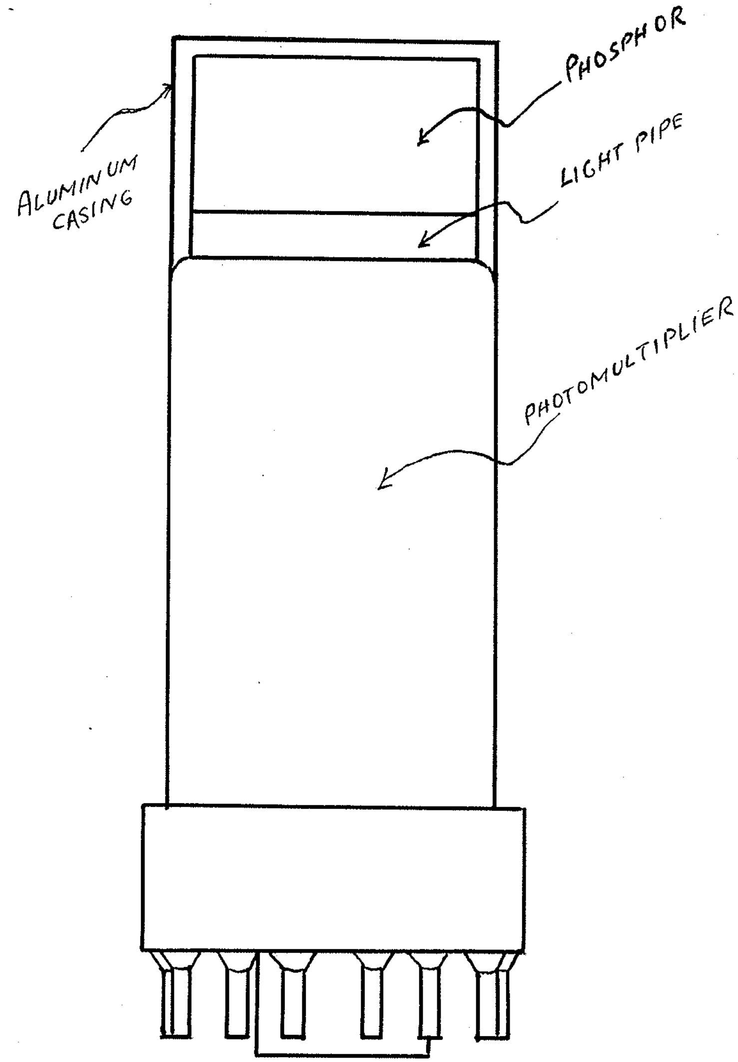

PHOSPHOR
LIGHT PIPE
ALUMINUM CASING
PHOTOMULTIPLIER

FIG. 1

plication process is repeated at subsequent dynodes, each of which is kept at a higher potential than the preceding one. Finally after a multiplication of the order of 10^6 to 10^9 the electron avalanche arrives at the collector plate. Thus the initial energy of a single ionising particle is transformed into a single voltage pulse, which may be used for detection and measurement. The amplitude of this pulse is directly proportional to the intensity of the flash subject to the statistical fluctuations in the multiplication process. The intensity of the flash from the scintillator is in turn proportional to the amount of energy lost by the γ-ray in the phosphor. This proportionality is also subject to statistical fluctuations (Roulston 1952) (Morton and Mitchel-1949)

Usually it is still necessary to amplify the pulses given out by the photo-multiplier. The amplifier also provides a simple means of varying the amplitude of the pulse without introducing undesirable effects provided the output varies linearly with the input signal. The resulting pulses may be measured in a differential discriminator generally called a Pulse Height Analyzer. This is an electronic instrument which allows only the pulses between voltages V and $V + \delta V$ to pass where δV is called gate-width. Keeping the gate-width constant and measuring the number of pulses as a function of V coming out of the pulse height selector, with the help of an electronic counter, one gets a scintillation spectrum. The block diagram of such a scintillation spectrometer is shown in Fig. 2, while Fig. 3 gives the γ-ray spectrum of Zn^{65} at 0.5 Volt gate-width taken by the author.

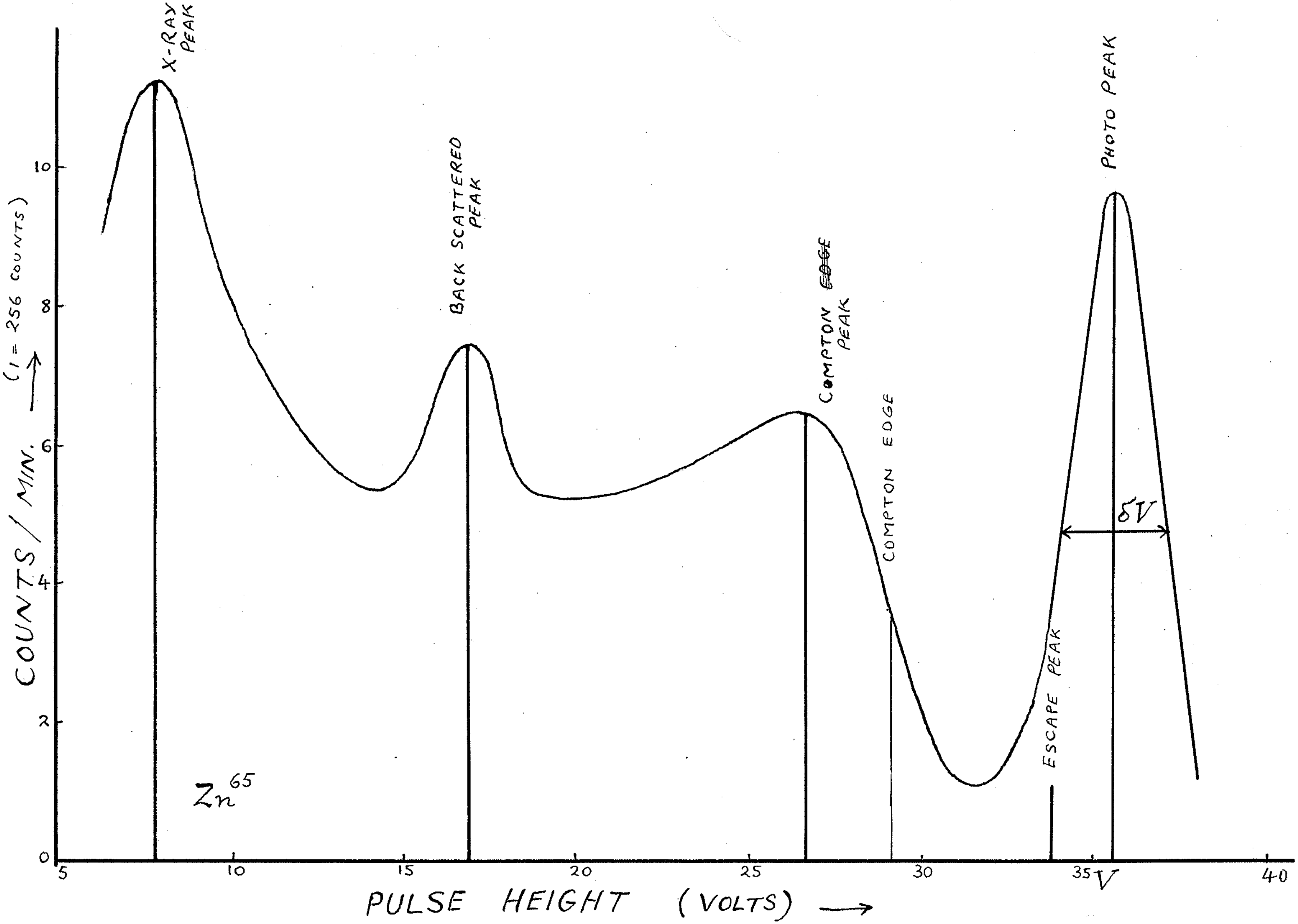

X-RAY PEAK
BACK SCATTERED PEAK
COMPTON ~~EDGE~~ PEAK
COMPTON EDGE
ESCAPE PEAK
PHOTO PEAK
δV
V
Zn^{65}
COUNTS / MIN.
(1 = 256 COUNTS)
PULSE HEIGHT (VOLTS)
0
2
4
6
8
10
5
10
15
20
25
30
35
40

FIG. ~~4~~ 3

APPLICATIONS OF SCINTILLATION COUNTERS

The development of photo-multipliers and the discovery of new scintillating materials has made the scintillation spectrometer an instrument of great importance in nuclear physics research. A range of phosphors has been developed each particularly suitable for the detection of one or more nuclear radiations. For example, for the detection of gamma rays the best phosphor known at present is sodium iodide activated with thallium, for α-particles the phosphor generally used is zinc sulphide activated with silver, while for β-particles, anthracene gives the greatest pulse height per unit energy expended in the crystal, but a number of commercially available scintillating plastics are also available. It should be noted that the best β-particle detector is sodium iodide but as it is deliquescent its use is restricted to the most specialized applications. The history of the application of scintillation counters is mostly the history of nuclear physics research. In most of the work done in this branch on the detection and measurement of energy quanta, the scintillation counter is one of the most important parts of the experimental arrangements. The credit for making this instrument so versatile in its applications goes mainly to the workers in the early period of the development of this instrument. Later experiments were chiefly the modified and improved versions of the same. An attempt will be made here to give an idea to the reader how widely the instrument has been used in almost every branch of nuclear physics with special reference to original workers.

The pioneer work of Coltman and Marshall (1947) and Curran and Baker (1948) showed α-particles to be very efficiently counted with a scintillation counter. With the proper selection of phosphor, the counter can be made insensitive to β-rays, γ-rays or neutrons and is more stable for long period measurements than a Geiger counter. Mann and Halpern (1951) used a similar instrument for the detection of protons from various (α,p) reactions. The ZnS screen effectively discriminated the γ-rays and scattered electrons from the betatron. Harding (1951), McCrary et al. (1954) and Berhman and Marinelli (1956) using scintillation counters detected neutrons efficiently. May and Thon (1951) used the scintillation technique for cosmic ray work while Richards and Hays (1950), Linlor and Regent (1953) and Scanlon et al. (1956) have used a scintillation counter detector for heavy ions and neutrons for use in a time of flight experiments.

Wouters (1949, 1952), Chamberlain et al. (1951) and several other workers used organic phosphors for the detection of high energy protons (100-350 MeV) from the synchocyclotron. Protons in neutron interaction were also measured with the help of scintillation technique by Johnson and Trail (1956) and Ribe and Seargrave (1954). Fast neutrons were efficiently detected by a scintillation counters by Fray (1950), Bell (1948), Harding (1951), Sharpe and Stafford (1951), Chamberlain and Easley (1954), Christie et al. (1956) and several other workers. Hofstadter et al. (1951) used the instrument for the measurement of thermal neutrons using a phosphor loaded with lithium.

In the spectroscopical measurements of heavy charged particles like protons and deuterons and by observing the recoil protons from a hydrogenous scatterer for high energy neutron spectroscopy, the scintillation spectrometers were successfully used and relatively good resolutions were obtained.

The scintillation counter was, however, found generally inferior to the proportional counter by Curran et al. (1949) for the β-ray spectroscopy of weak radiations but for energies greater than 200 KeV Bell et al. (1949, 1950) used the β-ray scintillation spectrometer with a single anthracene crystal quite successfully.

The very high efficiency of the scintillation counter for γ-rays makes it suitable for the measurement of very weak sources. Natural γ-ray activity of La^{138} has been successfully measured by Pringle et al. (1950) using a NaI(Tl) crystal and that of K^{40} by Sawyer and Wiedenbeck (1949). The high γ-ray detection efficiency of the instrument has also been applied in medical tracer diagnostic work. Cassen et al. (1950) have designed a directional $CaWO_4$ counter for the localization of I^{131} and Na^{24} Kohl (1951) devised a small phosphor photo-multiplier as a brain needle for the localisation of brain tumours. For studies of the biological effects of radiation Furst and Kallmann (1955) devised a bismuth loaded scintillation counter for the measurement of neutron dosage. Scintillation counters have also been applied by Peirson and Franklin (1951) and Pringle et al. (1950) for use in aerial prospecting.

In γ-ray coincidence measurements, the scintillation counter is particularly valuable. In addition to the very high γ-γ coincidence counting rate as compared to a gas counter, the reduction of the resolving time in the organic phosphors by a factor of 10^3 or more gives a corresponding reduction in the back-ground coincidence rate. The angular correlation of successive γ-rays emitted by six even-even nuclei (Co^{60}, Cs^{134}, Na^{24}, Sc^{46}, Y^{88} and Rh^{106}) were studied in the pioneer investigations of Bradley and Deutsch (1950) and the results obtained were found to be in agreement with the theory. Previous attempts to perform similar experiments with Geiger counters had been unsuccessful. For coincidence measurements of time intervals the scintillation counter was used successfully by Bell et al. (1952-1953). Fitch and Motley (1956) used this instrument for measuring the life of K-mesons. By using special scintillating materials the scintillation counter can be used (Reines et al.-1954 and Diven et al-1956) with very high efficiency in the coincidence measurements of neutrons.

MEASUREMENT OF GAMMA-RAYS

As mentioned before a scintillation counter has a very high efficiency for γ-ray detection and hence it is considered especially suitable for the counting of γ-rays. The γ-rays are always counted through the secondary electrons which they release. In Geiger counters and proportional counters the secondary electrons are practically never released except from the body of the outer electrode but as they are effective only when they are released close to the inner surface, these counters have an efficiency of approximately one percent. In scintillation counters, however, the phosphor can be made thick enough so that substantially all the γ-rays are absorbed and thus counted. Fig. 4 gives the efficiency for various crystal thicknesses and γ-ray energies.

The γ-radiation energy can be absorbed in various ways, and the γ-spectrum of a single energy will not be a single peak. The following will be the general features of such a curve from a source of a single γ-ray of energy E_γ (not much higher than one MeV) provided the source is not a positron emitter.

The number of counts corresponding to the absorption of the total energy E_γ of the γ-ray photon in the phosphor will go to form the main peak of the spectrum called the 'photo peak'. This total absorption of the energy E_γ can

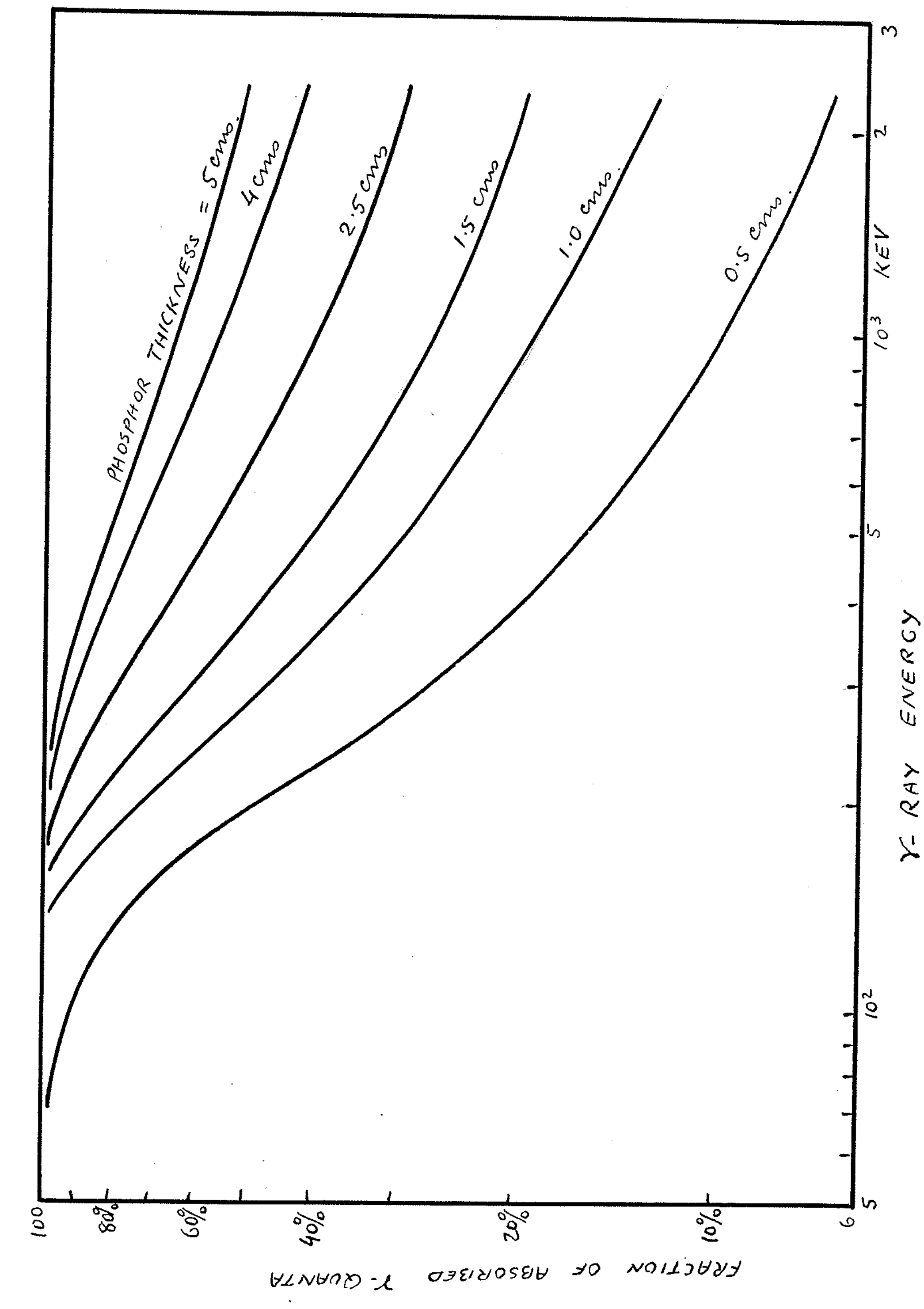

PHOSPHOR THICKNESS = 5 cms.
4 cms
2.5 cms
1.5 cms
1.0 cms.
0.5 cms.
100
80%
60%
40%
20%
10%
6
5
10^2
5
10^3
2
3
γ- RAY ENERGY KEV
FRACTION OF ABSORBED γ- QUANTA

FIG. 4

occur either by one single photo-electric interaction or by a number of Compton collisions followed by a photo-electric interaction and subsequenty absorption of the X-rays following every photo-electric process.

If the X-rays resulting from a photo-electric interaction are not absorbed in the crystal but escape from it, there will be another peak-called 'escape peak' with an energy $E_\gamma-(E_K-E_L)$, where E_K and E_L are the binding energies of the K and L electronic shells in an iodine atom assuming that the K-electron was knocked out in the photo-electric process, and the vacancy is filled from the L shell. X-rays produced in the subsequent filling of the L shell are totally absorbed in any moderately sized crystal. The escape peak therefore occurs 28.5 keV below the photo-peak.

Following the escape peak there will be a broad 'Compton portion'. This part of the spectrum corresponds to those γ-rays, which, after losing a part of their energy by the Compton process in the scintillation, manage to escape from it without further interaction.

On the basis of the relativistic laws of conservation of energy and momentum we can calculate the amount of energy imparted to an electron when the photon recoils straight backwards. This is the case when γ-quantum yields up to the electron the maximum amount of energy and retains an energy E'_γ. E'_γ is the least amount of energy the γ-ray quantum can have after a Compton process. This energy for a γ-ray of energy E_γ comes out

$$E'_\gamma = \frac{mE_\gamma}{2E+m}$$

where m is the mass of an electron in units of energy. Thus an electron receives at the most an energy of $E_\gamma - E'_\gamma$. This energy is called the 'Compton Energy'. The Compton Edge in Fig. 3 corresponds to this energy. Owing to the relatively large angular aperture of the crystal as seen by the source, the observed edge will appear at an energy somewhat lower than $E_\gamma - E'_\gamma$.

Some of the radiations backed scattered from the source or its backing due to Compton process will have a large probability of being totally absorbed in the crystal. It is obvious that in this case the γ-quantum will have an energy E'_γ. The absorption of this energy in the phosphor gives rise to another peak in the spectrum called 'Back Scattered Peak'.

The crystal will receive the back-scattered γ-rays other than those through exactly 180° and this will mean a smaller energy loss for these interactions. The back-scatter peak will therefore be observed at an energy somewhat larger than E'_γ.

There will be another peak corresponding to the X-rays emitted by the daughter nucleus in the source of γ-rays. These x-rays will arise due to internal conversion or K-capture if such is one of the modes of decay.

Fig. 3 shows the general shape of the spectrum from a source of single γ-ray energy (Zn^{65}) taken by the author.

SODIUM IODIDE SCINTILLATOR

Sodium Iodide, activated with thallium, combines a number of excellent properties which make it one of the most important scintillation phosphors. NaI(Tl) has about the highest energy conversion efficiency of any known phosphor, apart from zinc sulphide. It can also be grown into large single transparent crystals. The decay time at room temperature is 2.5×10^{-7} sec., which is shorter than most other inorganic phosphors and which is adequate for normal counting purposes. It is particularly suitable for the detection and measurement of γ-rays and X-rays. Also the rise time of a pulse obtained from a NaI(Tl) crystal is of the order of 10^{-9} seconds which makes it ideally suited for coincidence work whereas the rise time of a pulse in Geiger counter is about one micro-second.

RESOLUTION AND PULSE HEIGHT

Due to the very high γ-ray detection efficiency of the scintillation counter and the excellent qualities of NaI(Tl) for detecting and measuring γ-rays, further discussion will be confined to NaI(Tl)-scintillation photo-multiplier used in γ-ray spectroscopy.

It was observed that even when all the particles in the phosphor have the same energy, the pulses coming out of the linear amplifier are not of equal size. The finite pulse height resolution of the instrument, i.e., the spread of the output pulse distribution produced by mono-energetic particles can be explained as follows:

Each photon coming out of the phosphor has an energy of approximately 3 eV. Thus an absorbed ionizing particle of E_γMeV can release at the most $(E_\gamma/3) \times 10^6$ photons. In NaI(Tl) the number of photons emitted is about 10% of this number. If all these photons reach the photo-cathode only about 10% of these are found to release electrons. Thus in the case of a NaI(Tl) phosphor there are about 3000 E_γ electrons emitted from the photo-cathode of the photo-multiplier. In this number there is a statistical fluctuation of approximately the square root of this number. Hence even when all the ionizing particles, in the phosphor, have the same energy, the pulses coming out of the linear amplifier are not of equal size and the scintillation spectrum appears as peak A in Fig. 3.

It is desirable that the peak be as narrow as possible so that two peaks corresponding to two different energies, in the same sample lying close together should appear separate. As a measure of this quantity the 'Resolution' is taken as the percentage of the width 'δV' of the peak at half height divided by the pulse height 'V' at the centre of the peak:

$$\text{Resolution} = \frac{\delta V}{V} \times 100\%$$

Besides the inevitable statistical scattering in the pulse height, another widening occurs due to inhomogeneties in the phosphor, in the photo-sensitive layer of the photo-multiplier and in the optical bond between the two. In the case of γ-rays the pulse height, under steady conditions, is closely proportional to the energy of the γ-rays. Pulse heights corresponding to a number of γ-rays of different energies from various sources of approximately the same strength were taken by the author. Fig. 5 gives the variation of pulse height with energy.

As the gate-width is always finite the pulse spectrum is not measured exactly, but the spectrum is integrated over a certain interval. With every measurement the spectrum is smeared out, as it were, over the width of the gate. Fig. 6 shows the widening of the photo-peak as a function

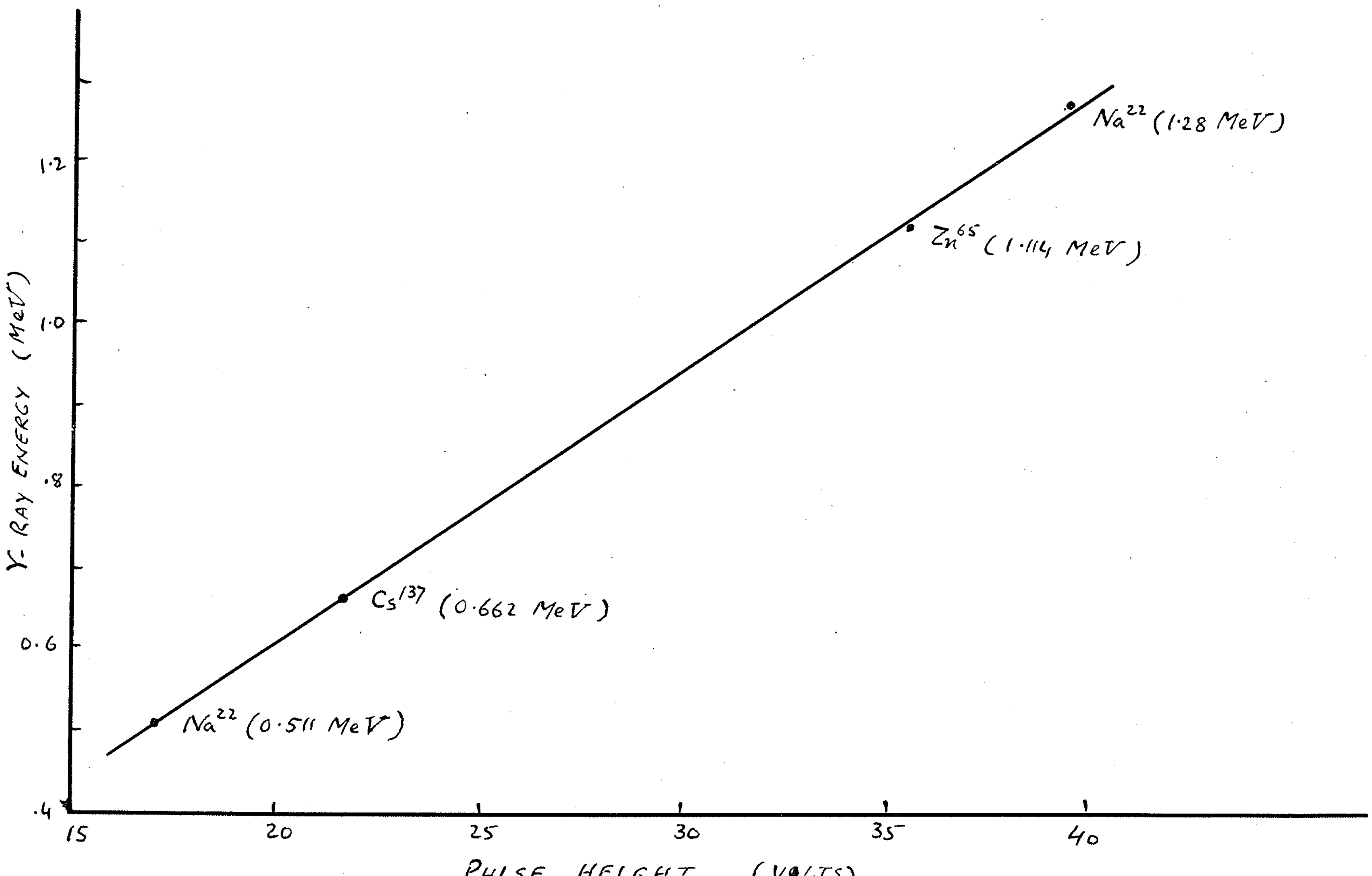

Y- RAY ENERGY (MeV)
1.2
1.0
.8
0.6
.4
15
20
25
30
35
40
PULSE HEIGHT (VOLTS)
Na22 (1.28 MeV)
Zn65 (1.114 MeV)
Cs137 (0.662 MeV)
Na22 (0.511 MeV)

FIG. 5.

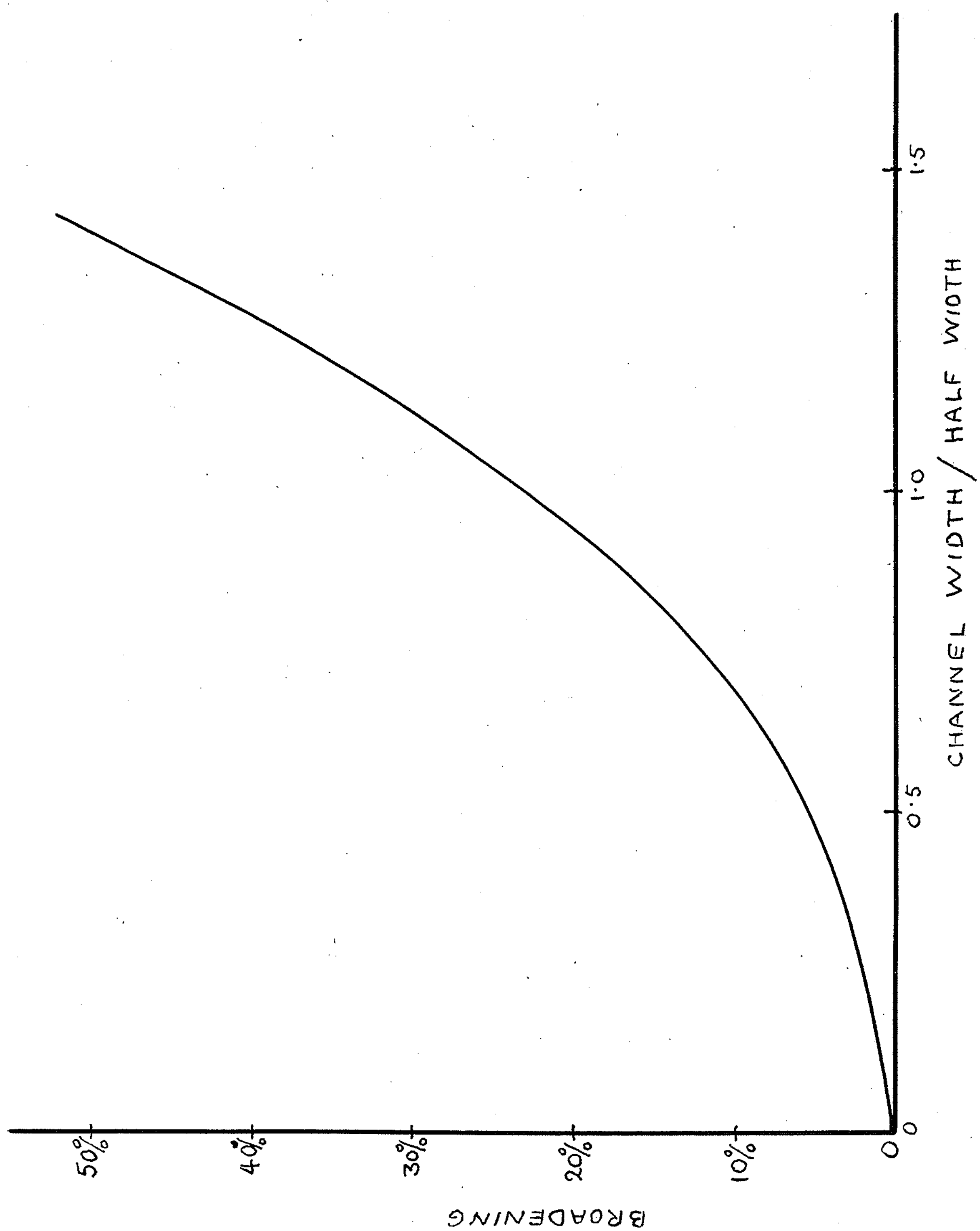


FIG. 6.

of the relative gate-width Wapstra (1954). Hence the gate should not be made too wide otherwise the details of the spectrum will get blurred. Also the gate width should not be made too narrow, because that way the counting rate is unnecessarily decreased.

INTRODUCTION TO PRESENT WORK

Since the discovery of the scintillation counting technique in the present form considerable improvement in the construction of photomultipliers has been achieved. For spectroscopic work DuMont tubes are generally favoured. On the basis of the principle of scintillation counting discussed before, it seems obvious that if the electronic devices used in the experiment remain steady, the gain (pulse height) and resolution of a particular photomultiplier, mounted with a particular phosphor, should depend only on the energy of the radiations interacting with the phosphor and the pulse height versus energy curve should be linear. But this does not appear to be the case. It has been known for sometime that conventional photomultiplier-sodium iodide crystal assemblies have been subject to changes in gain and resolution occasioned by external and internal effects other than the energy of the particles to be counted. The great importance of the instrument, in the modern nuclear physics research, attracted various workers to study the behaviour of a photomultiplier under varying conditions.

(a) The Effect of Counting rate

Caldwell and Turner (1954) first observed the dependence of gain on counting rate. They used two γ-ray sources. A 4-curie Po-Be source (4.5 Mev γ-rays and neutrons) was first placed 10 inches from the crystal to give 13 mr/hour. The base line setting for 4.5 Mev γ-ray was checked by taking a series of observations. When the base line setting of 4.5 Mev γ-ray was found constant another source of 10 mc of radium was then placed 6 inches from the crystal to give an additional γ-ray flux of 45 mr/hour. The base line setting of the 4.5 Mev γ-ray was then observed at regular intervals. A slow gradual increase in it was noted during the counting interval. In the same way by taking two sources of Cs^{137} of 100 mc and 5 μc and reversing the procedure of the experiment a slow decrease in the gain of the photomultiplier for 0.66 MeV photo-peak of 5 μc source was also observed. These experiments were performed using 1 1/2'' x 1 1/2'' NaI(Tl) crystals and DuMont-6292 and RCA-5819 photo-multipliers. For the 4.5 Mev γ-ray the increase in gain was at the rate of about 15% per hour after the radiation on the crystal was increased from 13 mr/hour to 45 mr/hour.

In addition to the slow change in gain mentioned above a rapid effect has also been reported by Bell, Davis and Bernstein (1955). Using DuMont-6292 photo-multipliers and a Cs^{137} source sudden changes in the gain due to a given radiation were observed as the counting rate was changed by increasing or decreasing the activity of the sample being counted by the crystal. Bernstein tried four DuMont-6292 tubes. Three of them showed an increase in the gain while the fourth one showed a decrease in the gain with the increase in counting rate. A number of DuMont-6363, 6364 and 6342 tubes were also tried and an increase in the gain with the increase in counting rate was observed while DuMont-5819 tubes showed no shift in the counting rate range used (60 to 7000 counts/sec). Trying different sources they have found that the change in gain (shift in pulse height position) was not the same at a constant integral counting rate for pulses of different energies. For the same change in counting rate the change in gain was less for low energy pulses than those of high energy pulses.

(b) The Linearity of Pulse Height versus Energy

The fluorescent response of sodium iodide crystals or the gain of the photo-multiplier with sodium iodide phosphor with radiations of different energies has been the subject of a number of experimental investigations. The conclusions drawn on the basis of the results obtained by various workers on the variation of gain with energy, however, are stikingly different. Pringle and Standil (1950) were the first to report non-linearity in the pulse height versus energy curve below 150 Kev with a curvature corresponding to higher gain at lower photon energy, while West et. al (1951), Erinsen and Jenssen (1952), Bannerman et. al (1951) and a number of other workers observed the gain to increase linearly with the energy of radiation from 1 kev to 650 kev. There does not appear to be any appreciable controversy in the variation of pulse height with energy in the energy range above about 200 kev but below this energy the situation still seems to be controversal. Taylor et. al(1951) reported a deviation from linearity in the gain versus energy curve below 1 kev but the curvature was in the opposite direction to that noted by Pringle and Standil while Freedman et al (1953) observed the same type of variation as Pringle and Standil in the range from 24 to 146 kev, as did also Bernstein (1956) for γ-rays below 200 kev energy. Engelkemeir, D. (1956) studied the variation of gain with energy from 10 kev to 1500 kev for NaI(Tl) crystal. He not only observed a pronounced deviation from linearity below 100 kev but found an appreciable nonlinearity over the entire range (10 to 1500 kev).

(c) The Effect of Temperature

Another factor found affecting the gain of a photo-multiplier is temperature but here again the results obtained by various workers do not agree. Van Sciver (1955) working in the temperature range from +20°C to -190°C using the normal type of NaI(Tl) crystal (10^{-3} mol fraction Tl) observed that the light emission intensity (gain) rises as the temperature is reduced from normal room temperature, reaching a maximum at about -130°C, and thereafter decreasing as the temperature is lowered further. Seliger and Ziegler (1956) studied the gain of photo-multipliers from -20°C to 30°C. He found an increase of response with temperature of 0.13% per degree centigrade for three RCA-5819 photo-tubes and an increase of 0.2% per degree centigrade for two DuMont-6292 photo-multipliers. Kinard (1957) studied the gain of a DuMont-6292 and RCA-5819 and 6655 photo-multipliers from -20°C to 60°C using a 0.125 μc Cs^{137} source. He used two tubes of each type and found that different tubes show different temperature sensitivities. The decrease in gain was found up to 40% with increasing temperature in the range from $-15^{\circ}C$ to $50^{\circ}C$. He, however, has not observed any change in the energy resolution of the system with temperature. Ball, Booth and MacGregor (1956) have also observed the decrease in gain with increasing temperature for RCA-6199 tubes in the same temperature range. The gain was found to decrease from 0.2 to 0.5% per degree centigrade.

(d) The effects of Magnetic Fields

There is practically no information in the literature dealing with the effects of magnetic fields on the performance of the photo-multiplier tubes. Customarily reference is made to the observation that the gain goes down if the tube is in a magnetic field. The only work of any size on this topic is an unpublished report from the University of Liverpool (England) which was communicated to us privately and deals with the behaviour of E.M.I. type-6260 photo-tubes. These tubes have the venetian-blind type of structure and therefore quite different from the DuMont type. There is a passing reference to the effect of magnetic field on multipliers used for mass-spectroscopy by Inghram et al (1953). There is, therefore, no volume of accessible information on this topic.

(e) Variation of Resolution with Energy

It has been known than even when all the particles interacting in the phosphor have the same energy, the pulses coming out of the linear amplifier are not of equal size. This variation in magnitude of the output pulses produced by mono-energetic particle was explained on the basis of statistical fluctuations in the various processes by which the energy dissipated in a phosphor is converted into a voltage pulse at the output of a scintillation counter. For a given photo-multiplier assembly the statistical fluctuations in the following processes are found to contribute to the spread of the output pulse distribution for mono-energetic particles.

1. Emission of photons by the phosphor.
2. Collection of the emitted photons by the photo-cathode.
3. Emission of photo-electrons by the photo-cathode.
4. Collection of photo-electrons by the first dynode and multiplication by successive stages.

Assuming that there is no thermionic emission of electrons in the counter and that the photo-cathode and dynodes are uniform and identical in response, Breitenberger (1955) has derived the following relation between the energy of the incoming particles and the fractional half width η (full width at half maximum) on the basis of statistical fluctuations occurring in the processes mentioned above:

$$\eta^2 = 8\ \ln 2 V_T + \frac{8\ \ln 2(1+V_M)K}{\bar{T}E} = \alpha + \frac{\beta}{E}$$

Where 'V_T' is the relative variance of the transfer efficiency, 'T' the probability of a photon producing a photo-electron, 'K' the mean energy required to produce a photon and 'E' is the γ-ray energy. This equation will be considered in more detail later.

Bernstein (1956), Kelley et al (1956) and Bisi and Zappa (1958) studied the variation of resolution with energy using 1 1/2'' x 1'' NaI(Tl) crystal. A detailed discussion of the results obtained by these workers will be given in the appropriate chapter. It will be sufficient here to mention that none of the results agree with the relation given by Brietenberger over the whole range of energy. Even among themselves, the results of Bernstein do not agree with those of Kelley et al and Bisi and Zappa.

(f) The Purpose of Present Investigations

A survey of the work done till now, on the variation of gain and resolution with both internal and external effects on the photo-multiplier scintillation assemblies, shows that either the work was not done in full details or there is a disagreement between various workers on the same effect. It was therefore considered desirable to study in detail the various factors influencing the gain and resolution of a photo-multiplier.

DESCRIPTION OF APPARATUS AND EXPERIMENTAL PROCEDURE

(a) Description of Apparatus

The main apparatus consisted of a conventional type of γ-ray spectrometer, the block diagram of which is given in Fig. 2. The power was drawn through a Sorensen A.C. Voltage Regulator Model 3000S. The Cathode followers used (five in all) were wired in the department using the conventional circuit. In all, three single channel Dynatron Pulse Analysers type N/101 were used during the progress of these experiments. Of the five linear amplifiers used, one was Hamner's Oak Ridge Model A-1D while four were laboratory made based on the Hamner circuit. The three low tension D.C. units used were also wired in the department. Two H.T. supplies, one Hamner Model 530 and one designed and made in this department were used. The scalers used in counting the pulses include two Glow Transfer counters AIC Model 162A, two TMC S6-3A Scalers and one Hamner Scale of 256 Model 201B. All the photomultipliers tried were DuMont types, viz, 6292 (four), 6364 (two) and 6291 (one). Optical coupling between the photomultipliers and the NaI(Tl) crystal was effected by Dow Corning Silicone 200 fluid of 10^6 centistokes viscosity.

In the study of magnetic field effects on photomultipliers, a small cathode follower using the conventional circuit was specially designed. The unit was so small that it could be easily positioned inside a solenoid built for this work. The casing and support of the cathode follower were made of a non-magnetic substance (Aluminium). The solenoid mentioned above was also specially made for this work. The solenoid was 60 cms long and 7 cms in diameter with four layers of 18 gauge copper wire windings giving 17 turns per cm. The above specifications were derived with the help of the well known relation

$$H = \frac{4 \pi n i}{10}$$

to obtain the magnetic field of about 100 oersteds along the axis of the solenoid for the maximum current of 5 amperes. The theoretical result was then checked by measuring the magnetic field with the help of a specially designed 2000 turn search coil and a fluxmeter. The linearity of the field was checked by passing the currents of different magnitudes in the solenoid and measuring the field in each case. The uniformity of the central field of the solenoid over the volume occupied by the photomultiplier assembly was checked by measuring the field at a number of places in that region for a constant current in the solenoid. The mild steel shield was made out of mild steel tubing of permeability of about 3550.

(b) Experimental procedure

Before starting any set of observations the electronic devices were allowed to settle for at least 12 hours. Each unit was continuously cooled by a fan in order to avoid over-heating of the electronics. Steady conditions were always checked by taking observations at an intervals of ten minutes for at least two hours.

The detailed description of experimental procedure in each experiment is given in the appropriate chapters.

EFFECTS OF COUNTING RATE CHANGES

As mentioned before Bell, Davis and Bernstein (1955) observed sudden changes in the gain of a photomultiplier as evidenced by a shift in the Cs^{137} peak when the counting rate was increased by bringing the source nearer to the crystal. Also a slow change was reported by Caldwell and Turner (1954) using two sources.

In the process of repeating these experiments a new effect has been observed. In addition to the sudden increase in the gain of a NaI(Tl)-photomultiplier when the counting rate is increased by decreasing the source-crystal distance, it has been observed that there is a slow creep of the position of the photo-peak to higher discriminator setting. This is not the same effect as observed by Caldwell and Turner but is similar in its manifestations. After the sudden change, the movement of the photo-peak is rapid at first and then slows down attaining a final steady position after three and a half or four hours. A similar type of decrease in the gain was also observed when the counting rate is suddenly decreased by increasing the source-crystal distance. These variations are shown graphically in Fig. 7 for a DuMont-6292 mounted with a 1'' x 1'' NaI(Tl) crystal using a Zn^{65} source and changing the distance from 10 inches to 4 inches in the first case and 4 inches to 10 inches in the second.

In order to be sure that the effect is associated only with the photo-multiplier, a number of precautionary

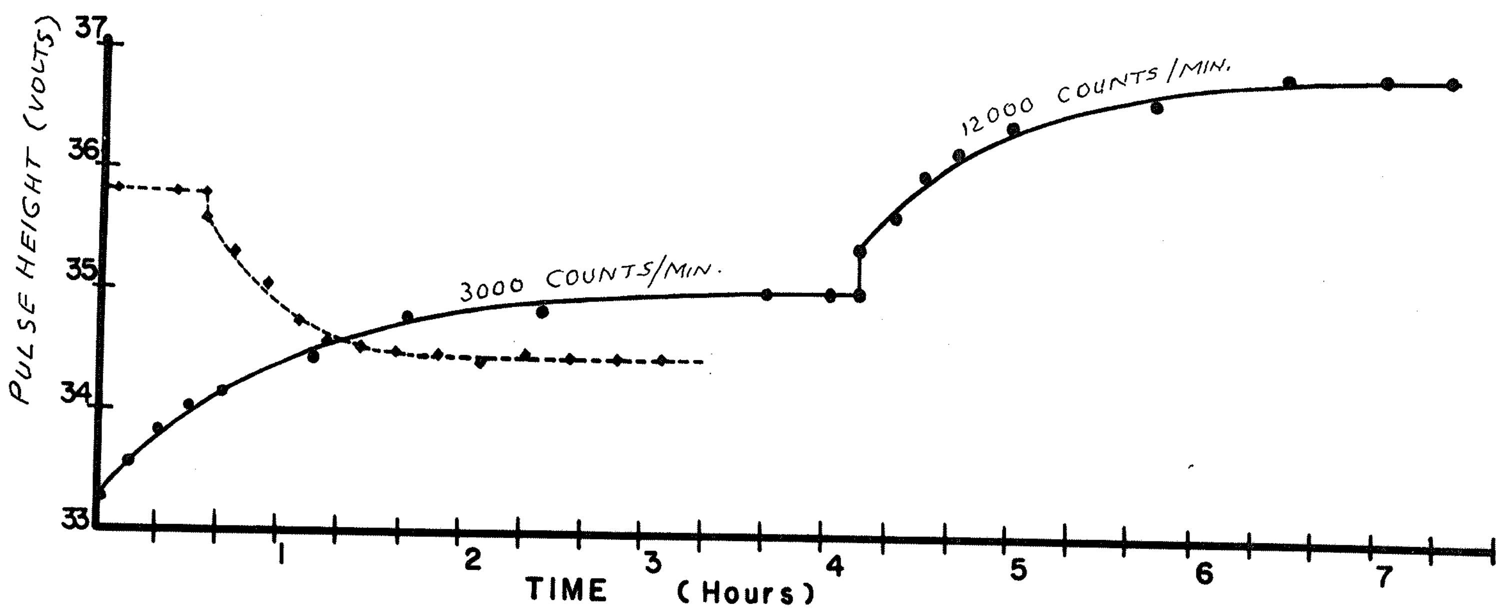

PULSE HEIGHT (VOLTS)
37
36
35
34
33
3000 COUNTS/MIN.
12000 COUNTS/MIN.
1
2
3
4
5
6
7
TIME (Hours)

FIG. 7

measures were adopted and numerous experiments were performed. To avoid fluctuations in the supply of the mains, the power was drawn through a Sorensen A.C.-Voltage Regulator. The overheating of the electronic devices was prevented by continously using a fan for each unit. In order to eliminate the effect of temperature on the photo-multiplier only those sets of observations were taken into account over which the changes in room temperature were not appreciable. The γ-ray beam was collimated by keeping the source in a 1/2'' diameter hole made in a 1 1/2'' x 1 1/2'' x 2'' lead block, the axis of the hole approximately coinciding with the axis of the photo-multiplier. The NaI(Tl) crystal was shielded from the sides by a lead cover of about 1/2'' thick, having a circular opening of about 1/2'' diameter in the side facing the source.

In order to confirm that this effect does not have its origin in the associated electronics a number of experiments with one DuMont-6292 mounted with 1'' x 1'' NaI(Tl) were performed. Changing one unit at a time, all the main electronic devices, like cathode follower, linear amplifier, pulse height selector and D.C. Voltage supplies were changed. The same photo-multiplier was then taken to another room and the same experiment was performed with entirely new set of electronic apparatus which was in use for another experiment altogether. The results obtained in all these experiments agreed within the experimental error. A further confirmation was done by feeding the pulses from a pulse generator, (of approximately the same magnitude as obtained from the photo-multiplier) into (a) the cathode follower and (b) the amplifier. No shift was observed in the position of the pulse height over a period of six hours from the commencement of this experiment other than minor statistical fluctuations. The observations were repeated a number of times by taking different amplifier, high tension and pulse height selector settings. All the experiments mentioned above confirmed the idea that the effect is entirely the property of the photo-multiplier assembly, and the effects were reproducible.

Before starting a set of observations the electronic devices had been allowed to settle for at least twelve hours with no source in the vicinity of the counter. Taking the results shown in the Fig. 7 as a typical example the experimental procedure and the derivation of results are described in the following paragraph.

After the electronic devices had been allowed to settle a Zn^{65} source was placed inside the source carrier at a distance of 10 ins. from the crystal. The reading of the position of the photo-peak of the 1.114 Mev γ-ray was immediately taken as determined by the single channel pulse height analyser with a 0.5 volt channel width. The position of photo-peak was then taken after every ten minutes for at least four hours. After the gain had been found to have reached its steady value, the source was then quickly moved to a distance of 4 ins from the crystal and the position of pulse height was recorded for a further period of about four hours as done before, taking readings after every ten minutes.

The counting rate of the photo-peak of the 1.114 Mev γ-ray was 3000 counts/min when the source was 10 ins from the crystal. Over a four-hour period the photo-peak moved from 33.25 volts to 35 volts to attain its steady value for this counting rate. When the source was moved from 10 ins to 4 ins the counting rate of the photo-peak increased to 12,000 counts/min. The position of the photo-peak was found to have shifted suddenly by about 1% and thereafter the long term variation set in reaching a final steady position in a further four hours period. In the increase of the counting rate of photo-peak from 3,000 counts/min to 12,000 counts/min. the shift in the peak position including the sudden change was observed to be about 2 volts from its previous steady level of 35 volts to the next steady value, a change of about 6%. In all four DuMont-6292, two DuMont-6364 and one DuMont-6291 tubes were examined. Tubes 6292 and 6291 were mounted in different combinations with two 1'' x 1'' and one 1'' x 1 1/2'' NaI(Tl) crystals, while DuMont-6364's were mounted with two 3'' x 2'' NaI(Tl) crystals. Optical coupling between the crystals and photomultipliers was done by Dow Corning Silicone 200 fluid of 1,000,000 Cs. The type of variation in gain with the counting rate was found the same as mentioned above but the actual magnitude of the shift varies considerably as between individual photo-tubes, an observation which further helps to confirm the belief that this effect does not have its origin in the associated electronics. For example one of the two 6364s showed practically no sudden or slow shift while all the others gave a variation similar to that shown in Fig. 7.

For a given γ-ray the final position of the peak pulse height varies linearly with the logarithm of the counting rate for a particular photo-multiplier assembly. A typical set of observations showing this is given in Fig. 8. For γ-rays of different energies the shift in the photo-peak for a particular photo-multiplier assembly is determined not only by counting rate alone but also by the energy, i.e., by the size of the individual scintillations. The effect is therefore dependent on the mean tube current.

Concurrently with the shifts in the position of the photo-peak, the changes in the resolution of the photo-peaks have also been noted. In every instance, as the photo-peak moves to higher discriminator settings with time the resolution improves. The improvement always exceeds that to be expected had the photo-peak been simply translated to higher discriminator values with preservation of its shape. It is clear therefore that the photo-peak narrows somewhat when the gain reaches its steady value, i.e., the statistical spread is reduced. A typical set of observations showing the variation of resolution with time as the pulse height shifts to higher discriminator values is given in Fig. 9.

It is not easy to understand fully the nature or the reasons for these effects. Space charge effects can be ruled out for there the gain would be expected to fall with increasing tube current, and further, even the highest

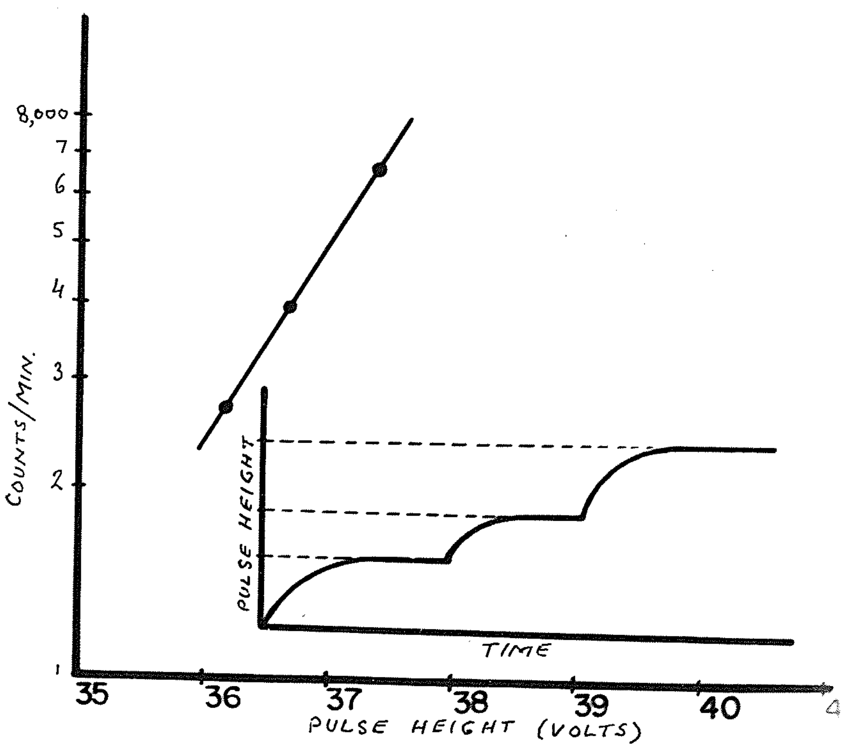

8,000
7
6
5
4
3
2
1
COUNTS/MIN.
PULSE HEIGHT
TIME
35
36
37
38
39
40
PULSE HEIGHT (VOLTS)

FIG. 8

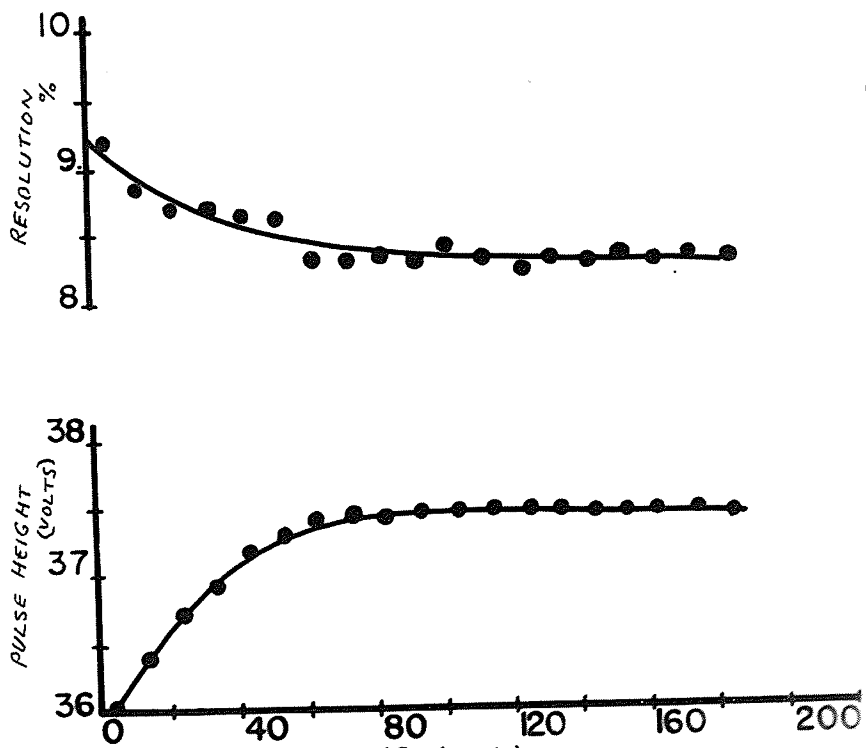

10
9
8
RESOLUTION %
38
37
36
PULSE HEIGHT (VOLTS)
0
40
80
120
160
200
TIME (MIN.)

FIG. 9

counting rates used in these experiments are well within the handling capacity of the tube and its associated electronic circuitry. Any counts lost at the photo-peak would serve only to widen the peak, not to make it more narrow as is observed. Also the effects of pulses piling up, the one on the tail of the other, would not cause an improvement in the resolution, even if the counting rates had been great enough to make this effect likely. Also it can not be regarded as an effect associated with electrode conditioning, for then, once having conditioned the dynodes to a certain bombardment a reduction in tube current by decreasing the counting rate, would not cause a drop in gain. It may be that this effect can be traced to the dynodes themselves, where under stronger bombardment the effective work function is reduced, perhaps by local heating. (The possibility of the effect associated with the crystal can easily be ruled out, for different tubes coupled to the same crystal produce shifts of different magnitudes). Cathey (1958) has stated, however, that current density and temperature do not change the secondary emission ratio of the dynode surface directly. The effect being examined by Cathey was the long term change in photo-multiplier gain known as fatigue and this has been shown to be due to the presence of cesium on the dynodes. The transfer of cesium between photo-cathode and dynode can not account for the effects described here for the changes in gain are reversible depending primarily on the momentary tube current. There has been no report that local dynode heating could increase its emissive properties.

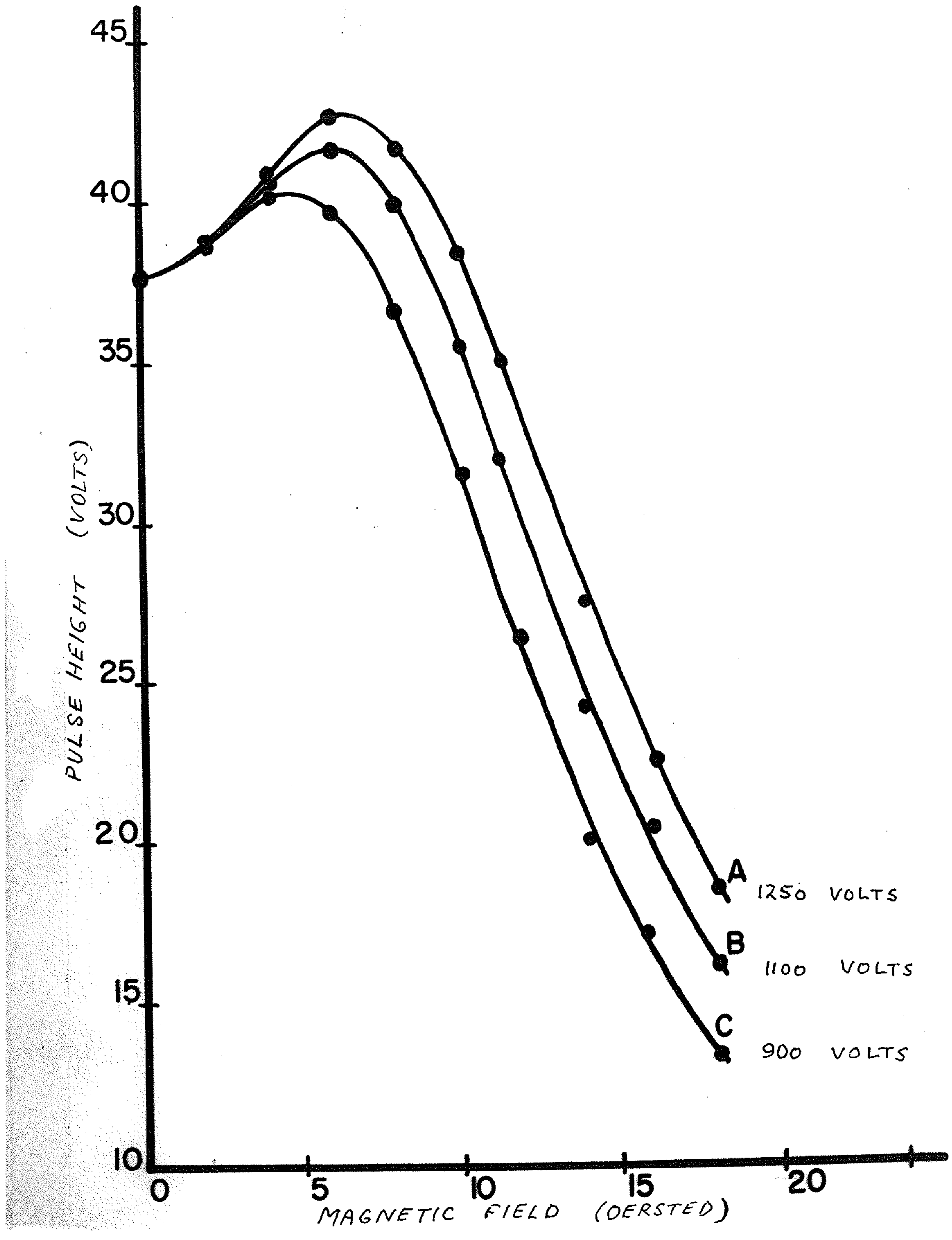
This effect is likely to cause apparent non-linearity in the response of scintillation counters and may well be (atleast in part) the cause of the widely differing opinions as to the linearity or otherwise of the voltage pulse from a photo-multiplier as a function of γ-ray energy as discussed in a previous chapter.

THE EFFECT OF AXIAL MAGNETIC FIELDS

In order to examine the effect of axial magnetic fields on DuMont-6292 photo-multipliers a small, non-magnetic cathode follower unit was constructed together with a solenoid 60 cms. long and 7 cms. inside diameter having four layers of windings. In this way the complete counting assembly could be positioned centrally in the solenoid and with energizing currents of 5 Amperes D.C. the counter could be subjected to a field of about 100 oersteds. Initial conditions showed the central field of the solenoid to be uniform to within 2% over the volume occupied by the photo-tube, that the field was linear with current and that a current of one ampere produced a central field of 20.3 oersteds. With the help of variable resistances it was possible to vary the current accurately in steps of 0.05 Amperes corresponding to steps in the magnetic field each of one oersted. The magnetizing current remained fairly steady during the experiment.

Prior to making a set of observations (with or without magnetic shielding for the photomultiplier) the entire assembly was demagnetized in the usual way by applying a decreasing alternating current of 60 cycles from the mains to the solenoid. This avoided possible errors due to residual magnetization in the metal parts of the photo-tube.

The variation in gain was found to be independent of the direction of the field with respect to the photo-multiplier tube. Fig. 10 shows this variation for an unscreened photo-tube to which is applied three different H.T. Voltages. The amplifier gain was adjusted to bring the photo-peak to 37.5 Volts in each case when the magnetic field was zero. It would appear that moderately weak fields of the order of few oersteds, introducing a spiraling effect in the electron trajectories produce a focussing action and hence a rise in gain of the photo-multiplier. This does not, however, last long for further increase in the field causes a rapid deterioration of the tube performance, the electrons being deflected to increasing extents away from their normal paths between successive dynodes. It was interesting to see if there was anything resembling a hysteresis effect in photo-multipliers of this type. The tube was subjected initially to a field of 20 oersted (point A in Fig. 11) which was reduced in steps to zero then reversed and increased to about the same value in the opposite direction (point F). The cycle of operation was then reversed until the field was back at its original magnitude and direction (point L). The letters on the graph in Fig. 11 denote the path of the cycle and the small asymmetry, showing that the scintillation counter tube (DuMont-6292) is slightly magnetic, is apparent.



45
40
35
30
25
20
15
10
PULSE HEIGHT (VOLTS)
0
5
10
15
20
MAGNETIC FIELD (OERSTED)
A 1250 VOLTS
B 1100 VOLTS
C 900 VOLTS

FIG. 10

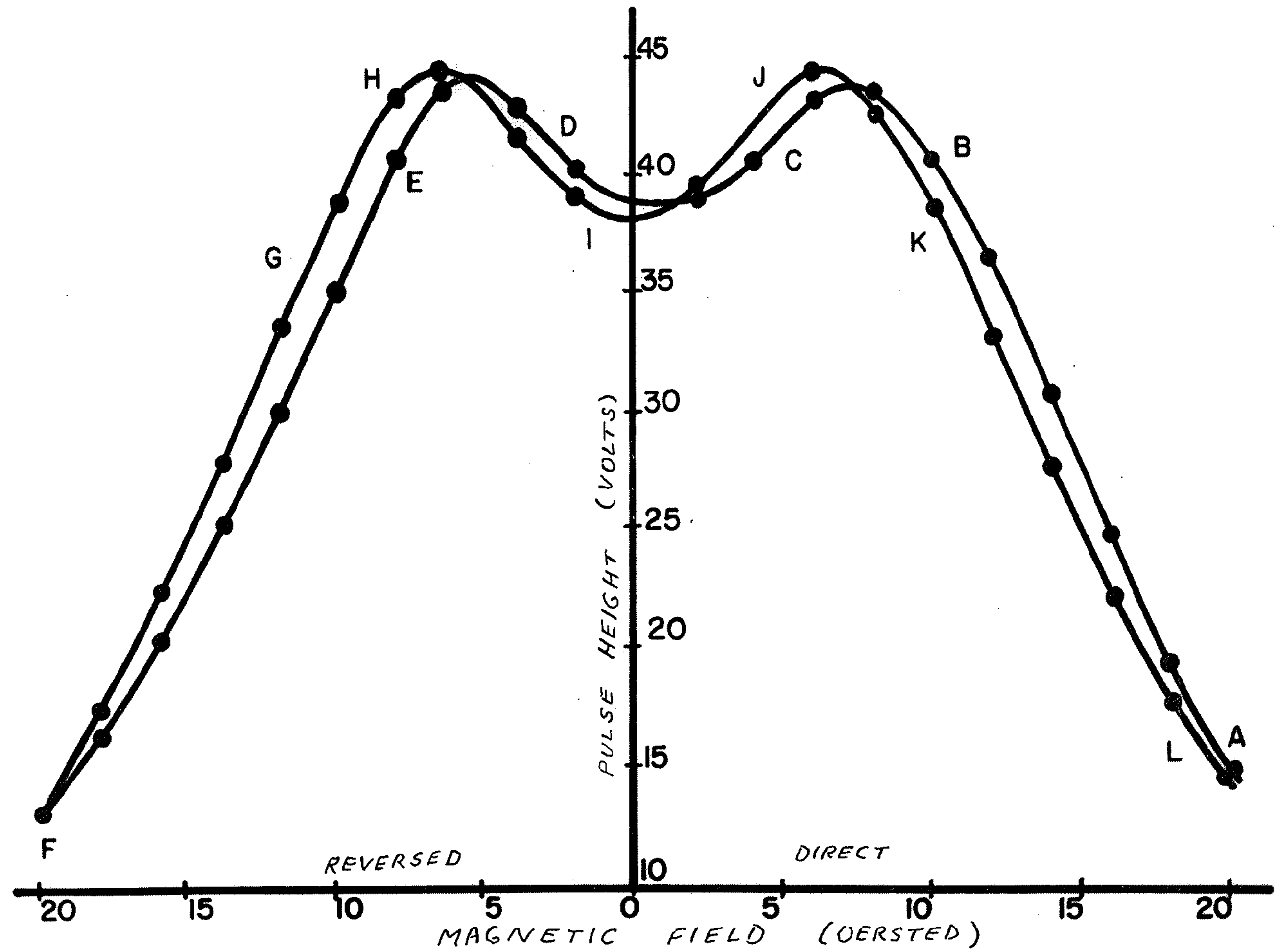

45
40
35
30
25
20
15
10
PULSE HEIGHT (VOLTS)
A
B
C
D
E
F
G
H
I
J
K
L
REVERSED
DIRECT
20
15
10
5
0
5
10
15
20
MAGNETIC FIELD (OERSTED)

FIG. 11

Because photo-multipliers have numerous applications in situations where magnetic fields are present, it was thought important to examine in detail the effectiveness of several methods of shielding. In Fig. 12 the performance of a DuMont-6292 photo-tube shielded with a commercially available mu-metal can is compared with that of the same tube unshielded. The can extended from the photo-cathode to a little below the top of the base, and it is seen to be relatively ineffective as a shield for axial magnetic fields. A number of additional tests were made using different lengths of mild steel pipe all cut from the same piece, and all having inside and outside diameters of 2.25 ins. and 2.50 ins. respectively. In Fig. 13 each curve is described by two lengths measured in inches. The first is the length by which the steel cylinder extends beyond the photo-cathode and the second is the length it extends below the junction of the glass envelope and the base. It will be noticed that as the length of the pipe extending beyond the photo-cathode is reduced from 7.5 inches the effectiveness of the steel pipe as a magnetic shield increases and then decreases, the optimum being obtained with this steel pipe extending approximately 2.0 inches beyond the photo-cathode and 1.9 inches below the junction of the glass envelope and the base. A little consideration will show that an optimum length of the shield is to be expected, for the induced magnetism will create a field within the steel cylinder in opposition to

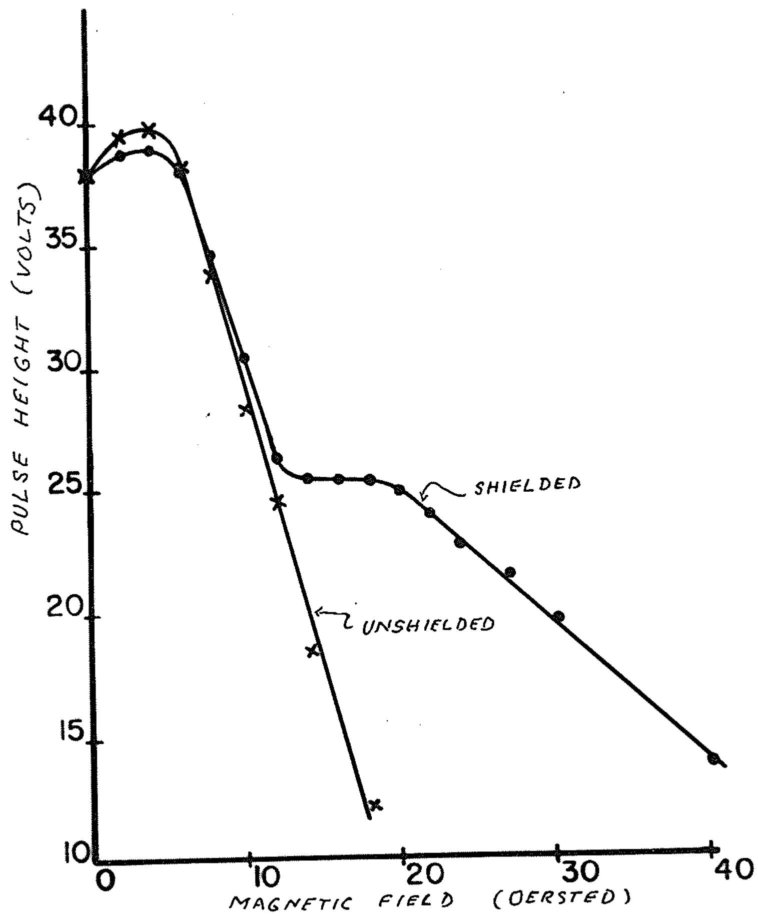
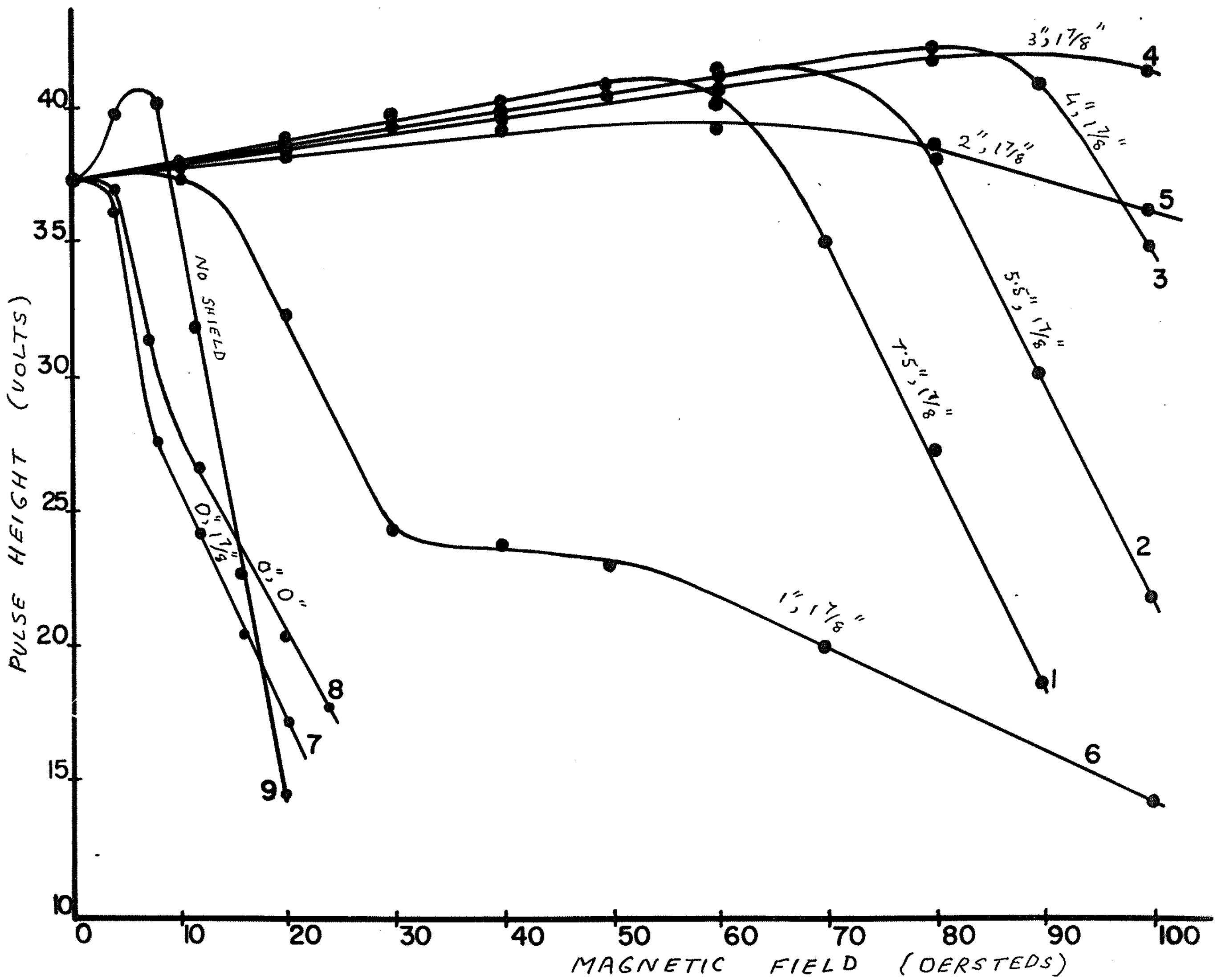

40
35
30
25
20
15
10
PULSE HEIGHT (VOLTS)
SHIELDED
UNSHIELDED
0
10
20
30
40
MAGNETIC FIELD (OERSTED)

FIG. 12



PULSE HEIGHT (VOLTS)
MAGNETIC FIELD (OERSTEDS)
10
15
20
25
30
35
40
0
10
20
30
40
50
60
70
80
90
100
3", 1 7/8"
4", 1 7/8"
2", 1 7/8"
5.5", 1 7/8"
7.5", 1 7/8"
1", 1 7/8"
NO SHIELD
0", 1 7/8"
0", 0"
1
2
3
4
5
6
7
8
9

FIG. 13

that of the solenoid. The actual degree of shielding will depend on the exactness of the cancellation of the two opposing fields, most particularly in the volume between the photo-cathode and the first dynode and this will be dependent on the value of the permeability of the steel, the relative positions of the ends of the steel cylinder with respect to the photo-multiplier tube and the length and diameter of the cylinder itself.

One recommended procedure for effective shielding reported by (I.R.E.Trans. Nuclear Science 1956) has been to extend the shield beyond the photo-cathode for a distance equal to the radius of the tube. From this study it would seem that a distance equal to the diameter would be more appropriate in view of the very rapid change observed between curves 5 and 6 of Fig. 13.

The change in resolution of an unscreened photomultiplier with axial magnetic field is shown in Fig. 14. It can be observed that the resolution has deteriorated along with the shift in gain of the photomultiplier as should be expected.

No information regarding the effect of earth's magnetic field on the gain and resolution of a photomultiplier could be obtained in the literature. The only available information on this topic was a private communication from Dr. S. Standil of the University of Manitoba. Using a DuMont-6364, he observed appreciable changes in the gain of a photomultiplier by reversing the position of the

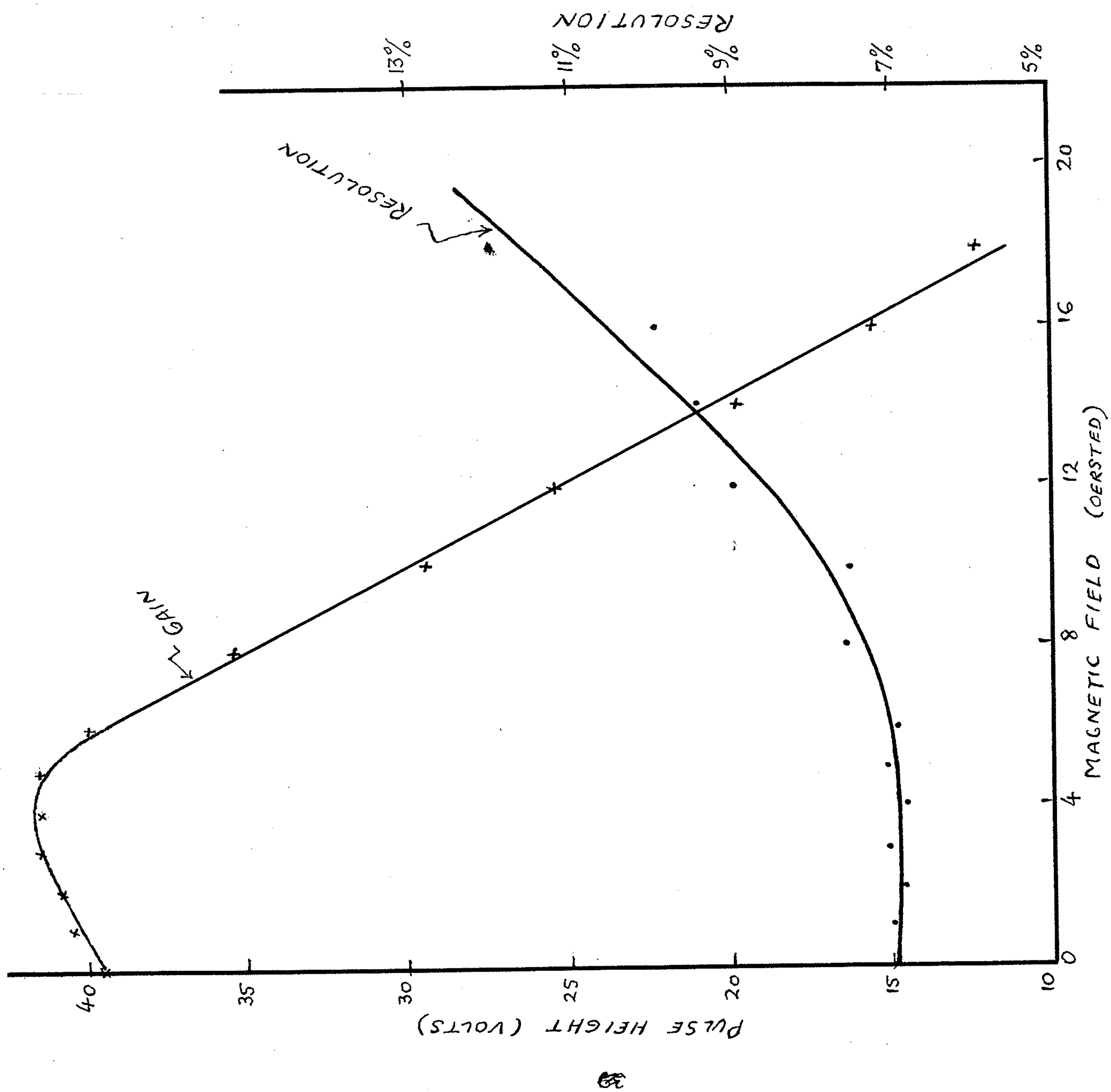

RESOLUTION
13%
11%
9%
7%
5%
RESOLUTION
GAIN
40
35
30
25
20
15
10
PULSE HEIGHT (VOLTS)
0
4
8
12
16
20
MAGNETIC FIELD (OERSTED)

FIG. 14

photo-multiplier along the direction of the earth's magnetic field.

In order to see if this effect was present in DuMont-6292 a number of experiments were performed.

Using a DuMont-6292 with 1'' x 1'' NaI(Tl) and Zn^{65} γ-rays the gain and resolution were studied by mounting the photo-multiplier assembly with the non-magnetic cathode follower pointing along the direction of the earth's total magnetic field then reversing the tube on the same axis. The same experiment was repeated for two mutually perpendicular orientations at right angles to the earth's field. Three DuMont-6292 tubes were tried but none of them showed any appreciable change in gain or resolution, irrespective of whether a mu-metal screening can was fitted to the photo-multiplier or not. These observations are in accord with the data obtained using solenoid produced fields.

THE EFFECT OF TEMPERATURE CHANGES

Whereas there is no general agreement as to the effect of temperature on photo-multipliers, the work of Van Sciver (1955-1956) has shown that for the normal type of NaI crystal used in scintillation work (10^{-3} mole function Tl), the light emission intensity rises as the temperature is reduced from normal room temperature, reaching a maximum at about -130°C, and thereafter decreasing as the temperature is further lowered. Several investigators reported the variation of multiplier gain with temperature around room temperature, but the results are quite conflicting. Seliger and Zeigler (1956) reported an increase of response of 0.2% per degree centigrade for two DuMont-6292's, while a third tube of the same type gave results somewhat lower than that. Kinard (1957) found a decrease in sensitivity of from about 0.1 to 0.5% per degree centigrade for the same type of photo-multiplier (DuMont-6292). According to him the gain changes are associated with the dynode structure rather than with the cathode.

The overall variation of a counting assembly is clearly due to the crystal and the photo-multiplier together. In the present work the variation of gain with temperature is found to be non-linear between 0°C to 35°C as shown in Fig. 15. For small variations around normal room temperature (20°C), the change in gain is found approximately linear

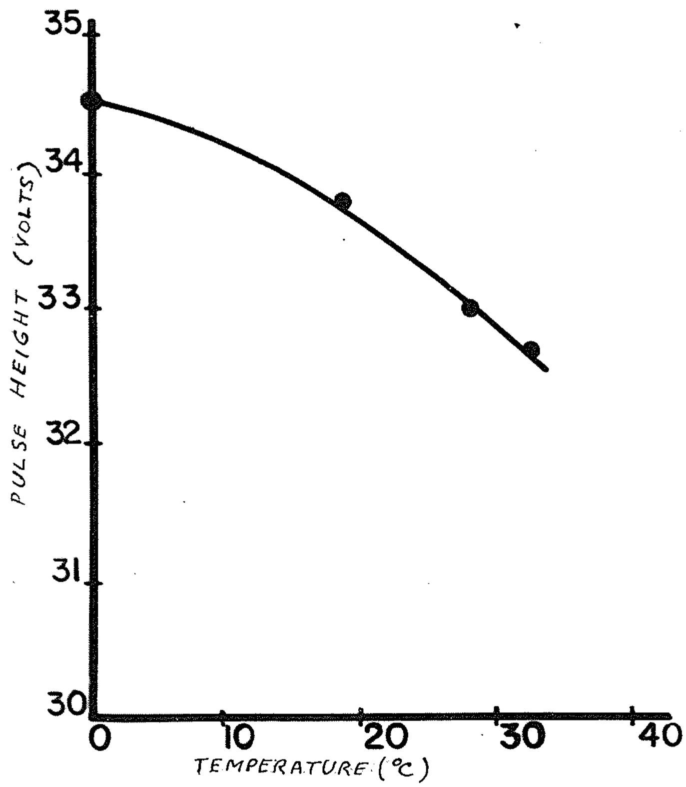


FIG. 15

with temperature, and is about -0.3% per degree centigrade for a 1'' x 1'' NaI(Tl) crystal and DuMont-6292 photo-multiplier. For a DuMont-6364 type of tube and a 5'' x 4'' NaI(Tl) crystal the corresponding value was found to be about -2.0% per degree centigrade. Such temperature effects are not negligible, and for work of the highest precision it is most desirable to operate scintillation counters at a controlled temperature.

No appreciable change in resolution was observed in the range of temperature between 0°C to 35°C.

Due to the poor conductivity of the photo-multiplier assembly the experimental procedure was found quite tedious. The photo-multiplier wrapped in a cellophane bag was first immersed in a glass container containing a mixture of ice and water and fitted with a stirrer and two accurate fractional thermometers. The photo-multiplier was kept in this condition by continuously adding ice and taking out water for about five hours. The pulse height position was also noted at different intervals. The final reading was taken when the pulse height position was observed constant for about two hours. The photo-multiplier assembly was then carefully taken out of the container and kept at room temperature. Readings at other temperatures were taken by adjusting the room temperature and keeping it approximately at the same level for more than six hours, always taking the final reading after observing the steady condition for about two hours.

An attempt was made to cool the scintillation counter to dry ice temperatures but this was unsuccessful. The crystal was found shattered after cooling had continued for some hours so further observations had to be abandoned.

THE RELATION BETWEEN RESOLUTION AND γ-RAY ENERGY

As mentioned in a previous chapter the spread of the output pulse distribution for mono-energetic particles is caused due to statistical fluctuations in the various processes by which the energy dissipated in a phosphor is converted into a voltage pulse at the output. The pulse starts with the interaction of incoming radiations with the phosphor. Only a part of the energy lost is stored in the flourescence centres and then converted into a light quanta. There may be fluctuations in the number of photons liberated per scintillation not only due to the normal statistical fluctuations but also due to the local variations in the luminescence efficiency of the phosphor. Of all the photons liberated in the phosphor, however, only a part reaches the photo-cathode. Some are absorbed in the phosphor itself and some are lost by absorption and reflection in the light guide. Here again the normal statistical fluctuation in the number of photo-electrons liberated by photons occurs. As successive scintillations do not take place at the same point in the phosphor the photon collection efficiency of the photo-cathode will be different for each photon of each scintillation. Some of the photo-electrons liberated from the photo-cathode are lost in the region between the photo-cathode and the first dynode. The normal statistical fluctuation in the multiplication process is therefore the sum of the fluctuations in the fraction of the photo-electrons collected by the first dynode and the variations of the response and collection efficiencies of subsequent dynodes.

Brietenberger (1955), assuming that there is no thermionic emission in the counter and that the photo-cathode and the subsequent dynodes are uniform and identical ~~dential~~, derived a theoretical relation between the energy of the incoming particles and the fractional half width η (full width at half maximum) on the basis of the statistical fluctuations mentioned above. Following is a simplified version of how he has derived this important relation.

The total number of electrons 'Q' received by the anode of the photo-multiplier is the product of the number of the photons 'X' and the probability 'T' that such a photon will produce a photo-electron from the light sensitive surface which succeeds in reaching the first dynode multiplied by the photo-multiplier gain 'M'. The amplitude of the output pulse is proportional to the quantity 'Q' and fluctuates about its mean value:

$$\bar{Q} = \bar{X}\,\bar{T}\,\bar{M}$$

with a relative variance 'V_Q' given by:

$$V_Q = V_T + (1 + V_M) / \bar{X}\,\bar{T} \qquad --- (1)$$

where V_T is the relative transfer efficiency. It is here assumed that the distribution is Poissonian i.e. that the mean value equals the variance or alternatively the reciprocal of the mean value equals the relative variance. The line shape of the photo-peak is not mathematically a

Gaussian curve but in practice it deviates so slightly from it that to a good approximation it can be described as such.

Taking the Gaussian error function plotted as the normal probability curve we get:

$$y = \frac{1}{\sqrt{2\pi}} e^{-t^2/2}$$

This has a maximum value at t=0 and falls to half value when $e^{-t^2/2} = 1/2$ or $t^2 = 2 \ln 2$. The square of the full width at half height 'y^2' is then $4t^2$ or $8 \ln 2$. The relative variance being equal to σ^2/S^2 is here equal to unity. $\bar{S}$ is the mean number of events.

In general then

$$\eta^2 = 8 \ln 2 V_Q$$

As here defined η^2 also represents the full width at half height when the γ-ray photo-peak is drawn in the usual manner. Also $\bar{X} = E/K$ where 'E' is the γ-ray energy and 'K' is the mean energy required to produce a photon in the crystal. And hence

$$\eta^2 = 8 \ln 2 V_T + \frac{8 \ln 2 (1+V_M) K}{\bar{T} E}$$

$$= \alpha + \beta/E \qquad \text{- - -(2)}$$

For the detailed discussion of the derivation of this relation the reader is refered to the works of Brietenberger (1955) and Bisi and Zappa (1958).

The dependence of resolution on γ-ray energy has been studied by Bernstein (1956), Kelley et al. (1956) and Bisi and Zappa (1958) using 1 1/2'' x 1'' NaI(Tl) crystals. All observed deviations from this law at energies $\gtrsim$ 0.500 MeV, the observed line width being less than that predicted by equation (2).

The following table gives the values of γ-ray energy and resolutions obtained by Kelley et al. (1956).

Energy (KeV) (E)	Resolution	η^2	1/E(Mev^{-1})
81	16.19	261	23.50
113	13.5	182	8.85
195	11.5	132	6.30
208	10.9	132	4.80
279	10.14	119	3.58
320	9.89	101.5	3.12
411	9.21	98	2.42
478	8.62	85	2.09
661	7.7	74.1	1.52
835	7.26	59.0	1.20
1067	6.56	43.0	0.92
1114	6.29	39.5	0.895
1277	6.07	34.0	0.785
1850	5.45	29.6	0.54

The variation of η^2 with 1/E is shown graphically in the figure 16. It can be seen that the slope of the graph suddenly changes at about 411 kev. Above this energy the resolution seems to improve.

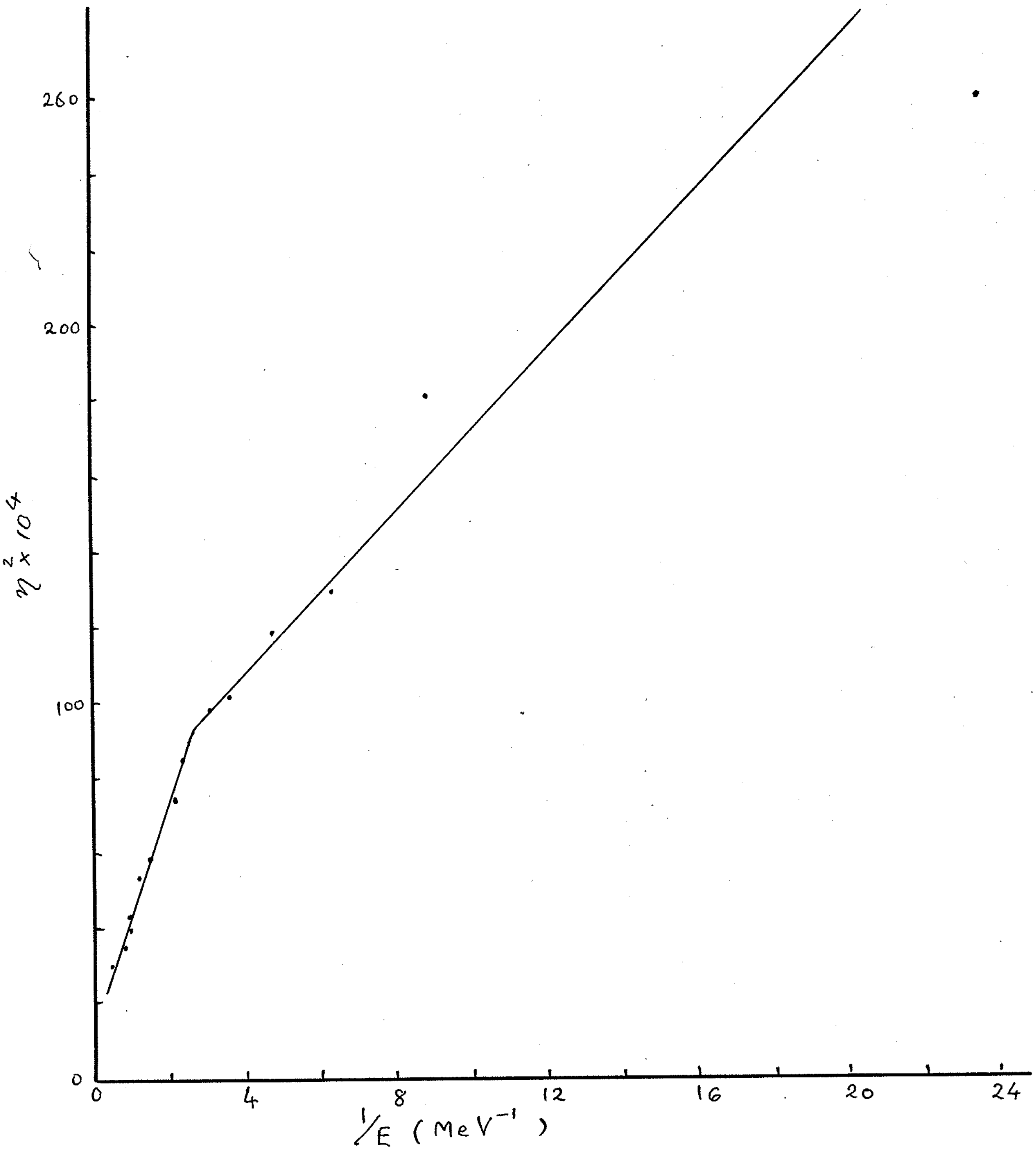
Bernstein (1956) does not tabulate his data but his graph is shown in Fig. . This is similar to Kelley's but the break occurs at about 150 kev.

The Oak Ridge group (Kelley et al.) have also presented a graph for a 3'' x 3'' NaI crystal coupled to a 6363 photo-multiplier which is definitely curved in shape and does not resemble any of those given for the smaller 1 1/2'' x 1'' crystals. (Mott and Sutton 1958; Nucleonics 14, 4, 46 1956).

Bisi and Zappa have also studied 1 1/2'' x 1'' NaI crystals. The graph showing their relation between η^2 and 1/E is shown in Fig. 17. The graph is linear up to about 0.5 Mev. Above this energy the graph shows a curve going downwards. Here again the resolution was observed to improve more than that expected on the basis of equation (2).

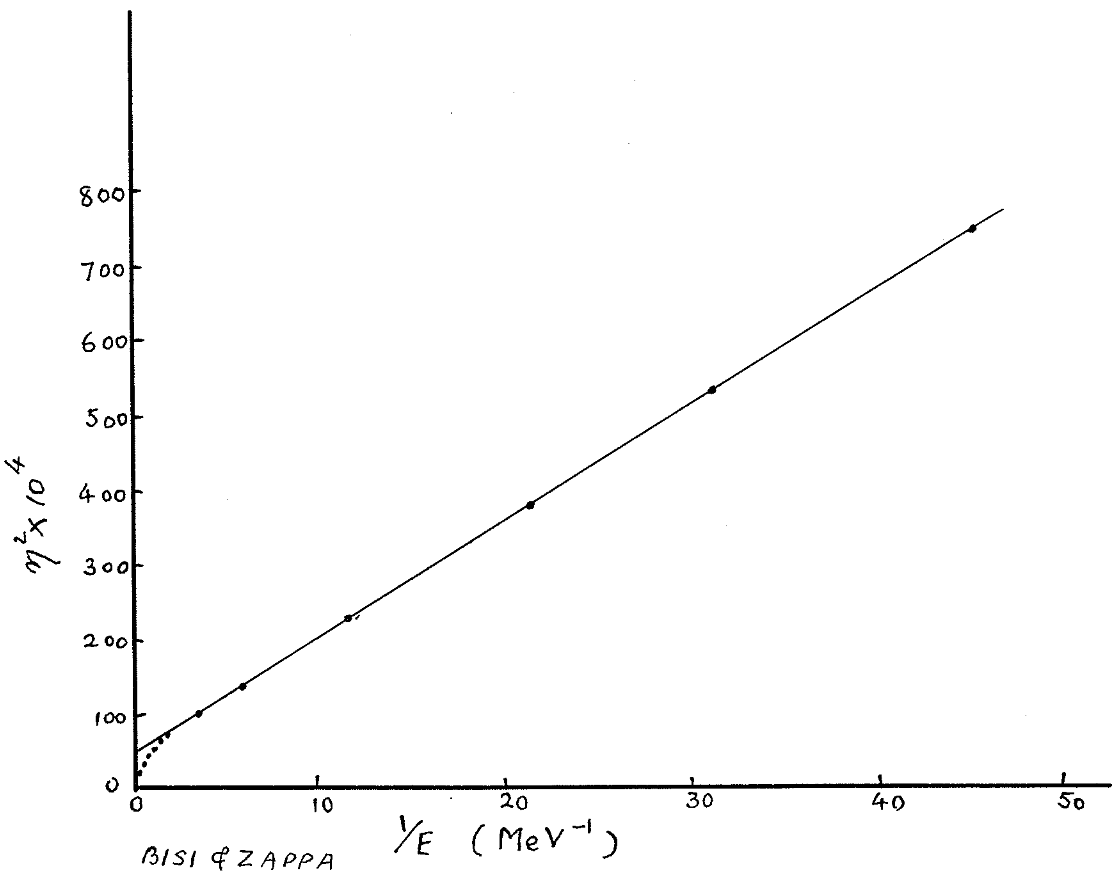
Bisi and Zappa, in order to explain the deviation have derived a relation showing that the width of a line corresponding to the absorption of a y-ray in a series of steps is narrower than that produced when the same y-ray is absorbed in one interaction.

If the energies E_1 and E_2 are absorbed in the phosphor simultaneously giving rise to a single photo-peak corresponding to an energy $E = E_1 + E_2$, assuming that the two



KELLEY

Fig. No. 16



800
700
600
500
400
300
200
100
0
$\eta^2 \times 10^4$
0
10
20
30
40
50
1/E (MeV⁻¹)
BISI & ZAPPA

FIG. No. 17

events are statistically independent, the relative half width of the observed pulse, calculated on the basis of equation (2), comes out to be:

$$\eta^2 = \alpha\left(1 - \frac{2E_1E_2}{(E_1+E_2)^2}\right) + \frac{\beta}{E_1+E_2} \qquad \text{---} (3)$$

It is clear that the width of this summation peak is smaller than the width of a photo-peak due to the absorption of only one γ-quantum of energy (E_1+E_2). η^2 reaches its minimum value for $E_1=E_2$

$$\eta^2 = \frac{\alpha}{2} + \frac{\beta}{2E_1} \qquad \text{---} (4)$$

The values of η^2 and $1/E$ obtained by Basi and Zappa agree excellently with the values derived on the basis of equation (3).

It will be clear that with small crystals there is no great body of agreement in the literature. Two groups which show the η^2 against $1/E$ dependence to divide into two straight portions disagree as to the energy at which the break occurs, while one group (Bisi and Zappa) observed a linear relation at low energies going into a curve at higher energies. It is therefore of interest to perform two experiments (a) with a small 1 1/2'' x 1'' crystal and (b) with a large crystal, say, 5'' x 6''. The first experiment would indicate whether or not the break occurred at the energies expected and whether or not the graph was a straingt line.

The second experiment would test the conclusions of Bisi and Zappa. If the observed improvement in resolution was due to multiple interactions at higher energies in small crystals, the substitution of a large crystal should greatly enhance the number of these multiple interactions because of the well known reduction of the Compton distribution relative to the photo-peak in such phosphors. If Bisi and Zappa are correct the large crystal should yield η^2-1/E graphs with pronounced deviations from linearity starting at a lower energy than that observed with small crystals. The results obtained are as follows:-

(a): $1\frac{1}{2}$"x1" Crystal

Energy MeV	η	1/E	η^2
0.511	11.76	1.957	138.29
0.662	9.89	1.510	97.81
1.114	7.22	0.8978	52.12
1.28	6.91	0.7813	47.6

The experiments were performed by taking three sources viz. Zn^{65}, Cs^{137}, Na^{22}. The variation of η^2 with 1/E is shown in Fig. 18. Results are in agreement with those of Kelley et al. and Bernstein.

Only four points were obtainable at this time (all > 500 keV) owing to the non availability of suitable sources of γ-rays of lower energy. However the linearity between 0.5 and 1.28 MeV energy shows a result at variance with the findings of Bisi and Zappa.

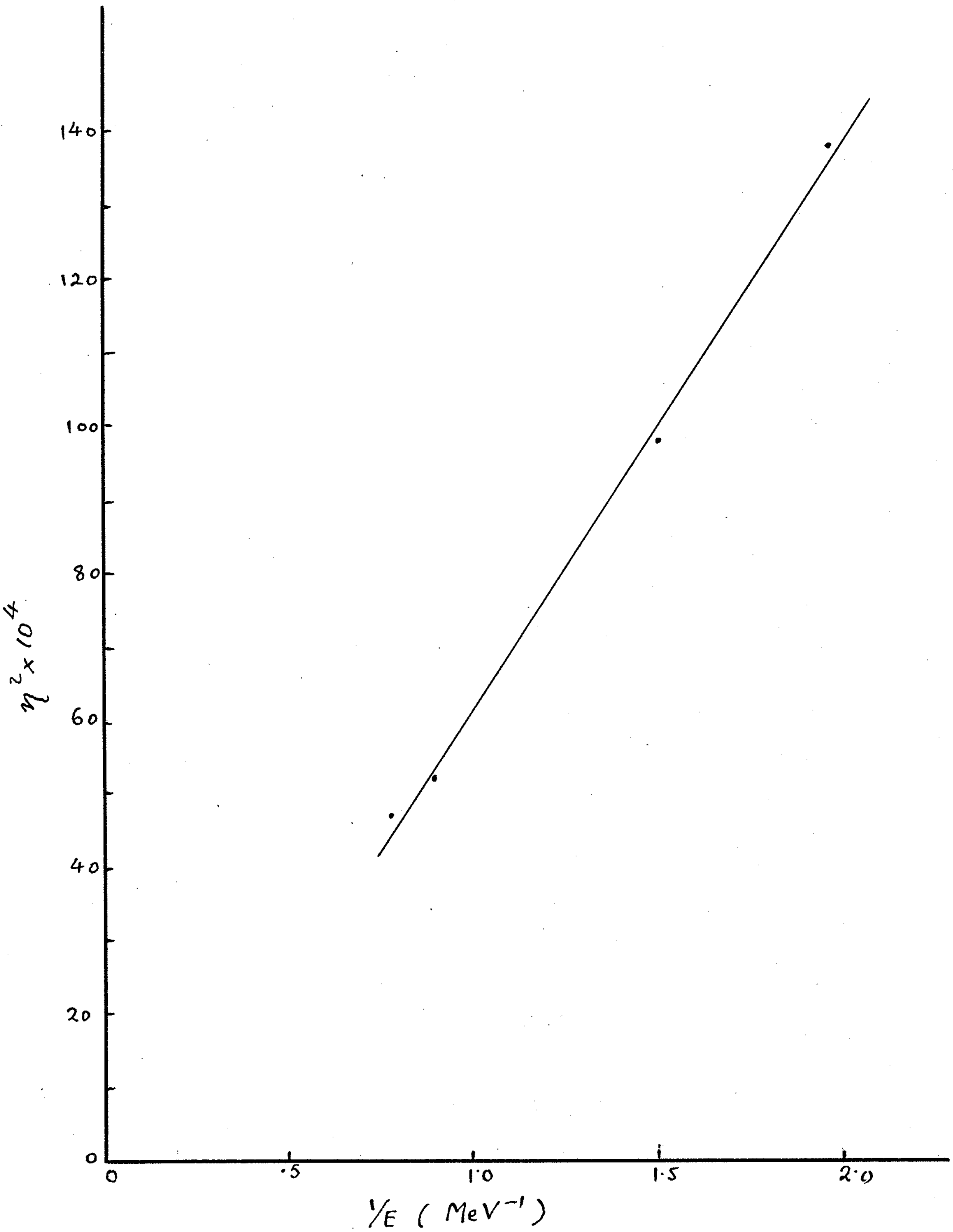


FIG. No 18

(b) The experiment with the large crystal was performed with a larger variety of sources giving a greater range of energies. The observations were made at A.E.C.L. Chalk River where the crystal and the sources were available and the data analysed in Winnipeg. The data were as follows:-

Source	E(MeV)	η(%)	η^2	$1/E(meV)^{-1}$
Am^{241}	0.0596	32.68	1055	16.8
U^{239}	0.0740	27.11	735	13.5
Lu^{177}	0.113	21.33	455	8.85
Lu^{177}	0.208	16.89	285	4.8
Hg^{203}	0.279	14.96	224	3.58
Na^{22}	0.511	11.70	137	1.96
Cs^{137}	0.660	9.80	96	1.515
Co^{60}	1.17	8.4	70.56	0.855
Na^{22}	1.28	8.2	67.23	0.78
Co^{60}	1.33	7.40	54.75	0.752

The graph is given in Fig. 19, and it will be seen to be linear all the way. It should be recalled that the accuracy is least good at larger values of η^2 and 1/E.

If indeed the statistical analysis would indicate an improvement in the resolution over that predicted by equation (2) for γ-rays of higher energy some other factor must be entering which nullifies this improvement.

At this stage it was considered important to see if any tables of energy and resolution existed in the literature for large crystals. The literature was searched exhaustively

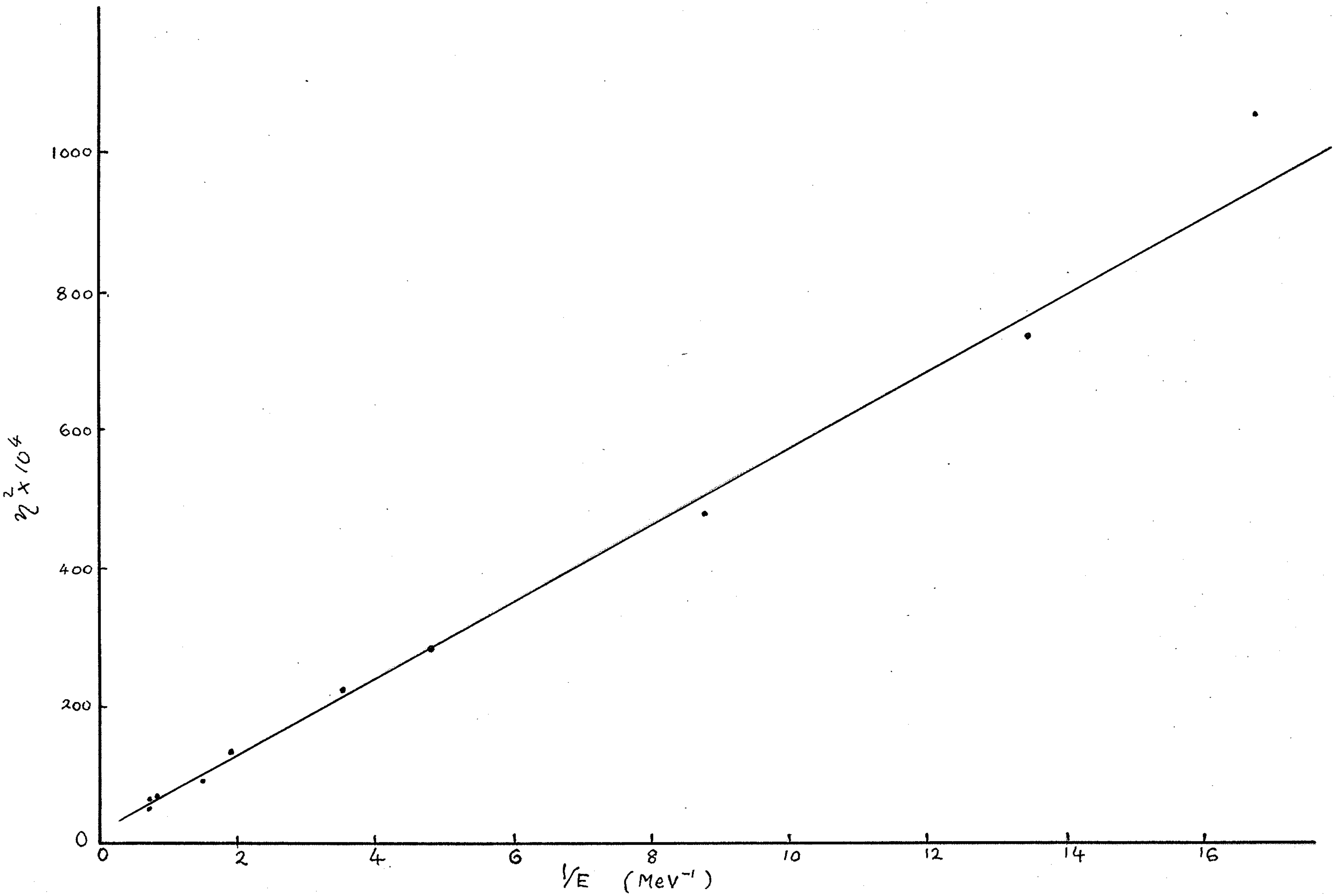


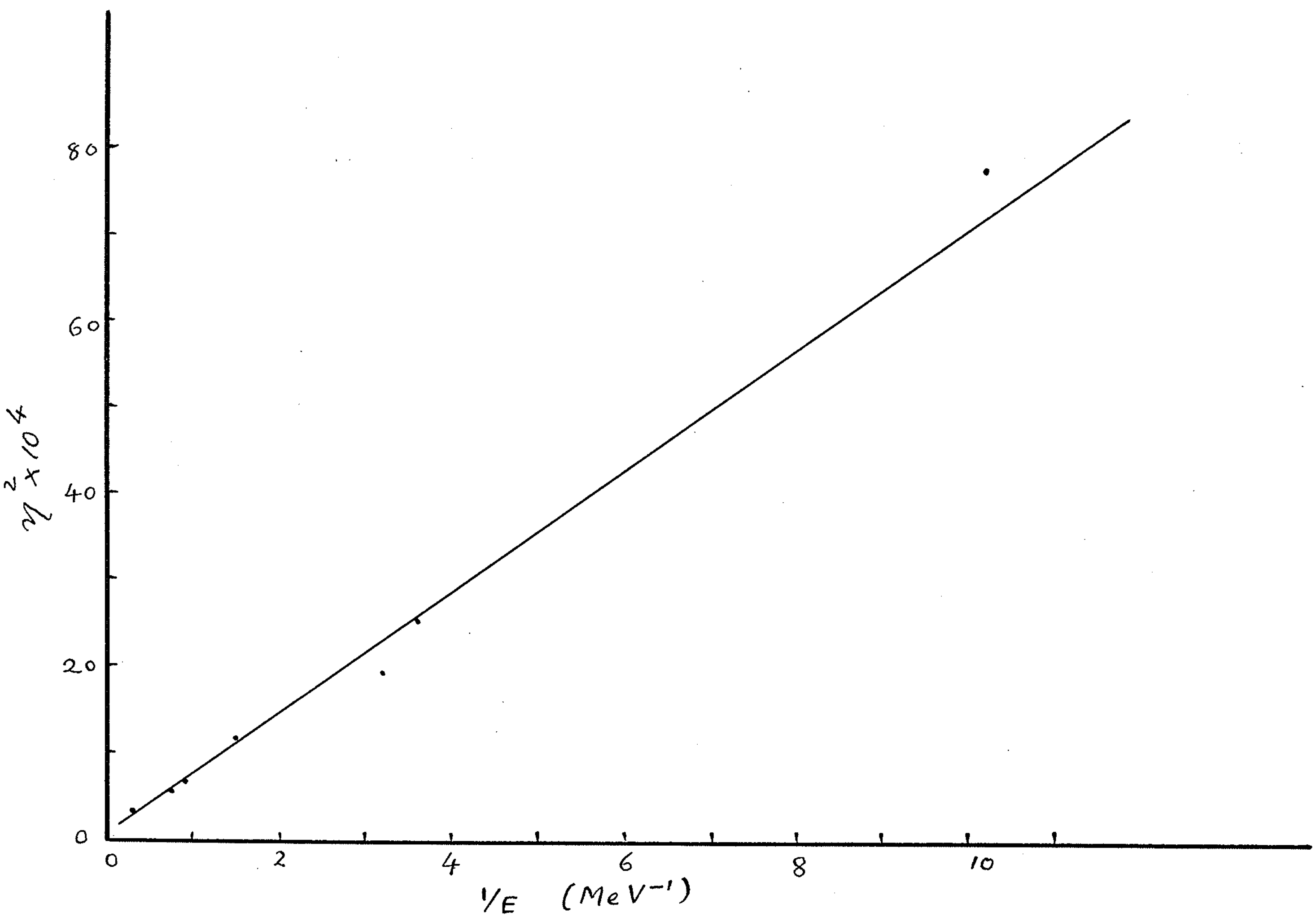
FIG. No. 19

and one such set of data for a 8'' x 5'' NaI(Tl) crystal was discovered (Koch and Foote 1954). The data were not in the form we needed so the observations were recalculated to give the following data:

Energy (MeV)	1/E(MeV^{-1})	Resolution	η^2
0.087	10.15	28	78
0.279	3.58	16	25.6
0.360	3.22	14	19.6
0.669	1.495	11	12.1
1.12	0.893	8.5	7.2
1.33	0.752	8.0	6.4
2.62	0.382	6.0	3.6

The variation of η^2 with 1/E is shown in Fig. 20. and shows a linear variation which is in agreement with our results.

A number of conclusions can be drawn from these observations. It may well be said that large crystals are likely to be less uniform in their scintillation efficiencies than small ones, and there is more opportunity for local variation in the thallium concentration. Alternately it could be that the scintillation variance is non-normal. To obtain the Poisson distribution in the number of photons in a scintillation (which is postulated in the derivation of equation (1)), the excitation energy must be given in a random fashion to the luminescent centres. If this randomness is not achieved, the full expression for V_Q must be used, viz.



FOOTE & KOCH

FIG. No. 20

$$V_Q = V_T + (1 + V_T)(V_X - \frac{1}{\bar{\bar{X}}}) + \frac{1+V_M}{\bar{\bar{X}}\bar{\bar{T}}} \quad - - - (5)$$

(Breitenberger 1955) and it will be seen that the additional term could be positive. Any deviations of V_X from the normal value of $1/\bar{\bar{X}}$ would be expected to be more pronounced at higher γ-ray energies. This feature of the scintillation process has received little or no attention in the past and there is apparently no available data which would indicate whether or not the distribution of 'X' is normal or not in the case of scintillations from NaI(Tl). Another possible explanation for the controversy over the variation of η^2 with 1/E can be the use of sources of different intensities by a worker as this will also cause variations in η^2 for the same 1/E as has been shown earlier in this work. The situation can be summed up as follows.

Either Bisi and Zappa's interpretation of the statistical effects are in error and the true relation between η^2 and 1/E is a linear one with unexplained effects causing an improvement in the resolution at low energies or their interpretation is correct and some effect such as a non-normal variance in the scintillation process becomes apparent in large crystals which effectively nullifies the improvement in resolution and yields a straight line relation by chance.

Be this as it may the results obtained by us and Koch and Foote for large crystals being different from previous experience with small crystals would indicate that further tests are required on crystals of a variety of sizes to settle this matter unequivocally.

CONCLUSIONS

The main conclusions, on the basis of the work submitted in this thesis, for various effects influencing the gain and resolution of a scintillation NaI(Tl) counter using DuMont type photo-multipliers can be summarised as follows:-

(a) Effect of counting rate

The gain of the photo-multiplier varies with the logarithm of the counting rate for a particular energy of the γ-ray. For a particular counting rate the variation is proportional to the energy of the γ-quantum. For reliable results the counter should be kept counting for at least four hours before taking any observation.

For the work where more than one source is to be used the intensities of the sources should be such that the tube current in each case remains the same.

The results of Bell, Davis and Bernstein were confirmed together with a slow increase in gain with time becoming steady after about four hours.

(b) Effect of axial magnetic field

There is no appreciable effect of earth's magnetic field on DuMont-6292 tubes. On the otherhand for fields over few oersteds the gain and resolution deteriorate rapidly with increasing magnetic fields. The commercially available mu-metal shield is practically useless as a shield for axial magnetic fields. The best shielding is achieved when the shield projects beyond the photo-tube equal approximately to its diameter.

(c) Effect of temperature

There does not appear to be any change in the resolution of a photo-multiplier with temperature around room temperature. The results obtained for the variation of gain of a photo-multiplier with temperature by various workers do not agree. It, however, seems that around room temperature the gain decreases with increasing temperature and may be as high as 2% per degree. It is therfore advisable that for accurate works the room temperature should be kept approximately at the same level over the entire period during which the observations are taken.

(d) Variation of Resolution with energy

This effect is discussed in detail in the previous section and it will be seen that there remains an unresolved conflict as to why a linear graph of η^2-1/E is obtained for large crystals.

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